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R/P065

design of photomultiplier output circuits for optimum amplitude or response

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1 introduction

The purpose of this paper is to explain the various ways in which the output signal from a photomultiplier is best handled. This question can only be answered by first investigating the following two relevant topics: the nature of the optical signal at the photocathode and the characteristics of the photomultiplier output signal.

The number of applications calling for the use of photomultipliers is extensive and includes, for example; low level photometry; astronomical observations; fast coincidence systems; atomic and molecular spectroscopy; film scanning and scintillation counting. A signal processing system designed for a particular application is rarely suitable for direct use on a different application. It is not feasible to attempt a comprehensive treatment here and a deliberate choice in favour of pulse handling circuits has been made. Consider, for example, the light emission from scintillators. This is not excessively restrictive since the exponential like decay of the optical signal refers to other applications as well; the pulse shape of the output from a fast photomultiplier when excited by a) Cerenkov light b) single photons or c) scintillations from certain plastic materials, is very similar. The data of **table 1** summarises the properties of various scintillators and indicates quite clearly both the large range of decay times and signal levels which must be accommodated. The figures for the expected number of photo-electrons refer to small, optically coupled phosphors. Where large area/volume scintillation and Cerenkov counters are concerned, onaly a small fraction of the light is collected by the photomultiplier and the expected yield is typically in the region of 1-10 photoelectrons MeV^{-1}. Referring to the data of **table 1**, it is clear that output circuits will be required to handle signals, which at the input to the photomultiplier, extend over a dynamic range of 10^4 photoelectrons and with decay times of 1-230 ns. Hence, for example, the electronics required for a NaI(Tl) system will be different from that required for a counter using a plastic scintillator.

2 photomultiplier output signal

The appropriate equivalent circuit for the output of the photomultiplier is a **current generator** I(t), in parallel with output resistance R_o and capacitance C_o. The photomultiplier is perhaps the device which more than any other conforms to the definition of an ideal current source with R_o in excess of 10^{12} Ω and C_o in the range of 5-20 pF. The magnitude of C_o depends on the type of tube used and the ciruit layout. The following analysis shows how this capacitance together with the anode load resistance determines the nature of the output signal. Consider light output with an exponential decay in intensity, with a single time constant τ_s.

The photoelectron current i(t) is therefore given by

$$I(t) = \frac{Ne}{\tau_s} \exp(-t/\tau_s) \qquad ...(1)$$

where N is the total number of photoelectrons and $e = 1.6 \times 10^{-19}$ C. For an ideal photomultiplier of gain G, the output current I(t) is given by

$$I(t) = G.i(t) \qquad ...(2)$$

Referring to **figure 1** we have that the output voltage is

$$V_o(t) = \frac{GNeg}{(\tau - \tau_s)} [\exp(-t/\tau_s) - \exp(-t/\tau)] \qquad ...(3)$$

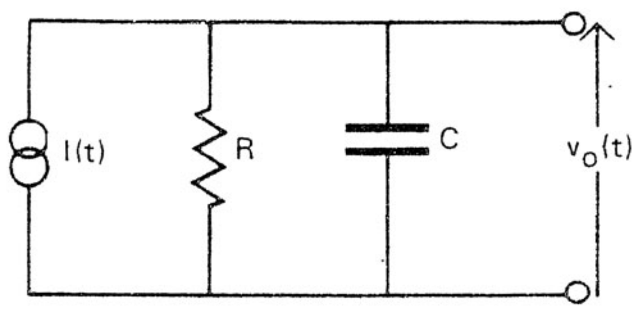

figure 1 equivalent circuit for the photomultiplier

where τ = C R is the output time constant, which includes the anode load resistance and any external combination of R and C in parallel, coupled to the output of the photomultiplier. **Figure 2** shows the results of the evaluating equation (2) for the following parameters: N=100, $G=10^6$, τ_s=5 ns, C=10 pF with R taken successively as 100, 500, 1k, 3k, 10k and ∞Ω (ie. τ=1 ns, 5 ns, 10 ns, 30 ns, 100 ns and ∞ns respectively). Equation (3) refers to the output pulse in the ideal situation whilst in practice

transit time spread in the photomultiplier also effects the pulse shape. Accepting this limitation, the curves may still be profitably used to predict the output signal in most cases. The information in figure (2) may be summarised as follows:

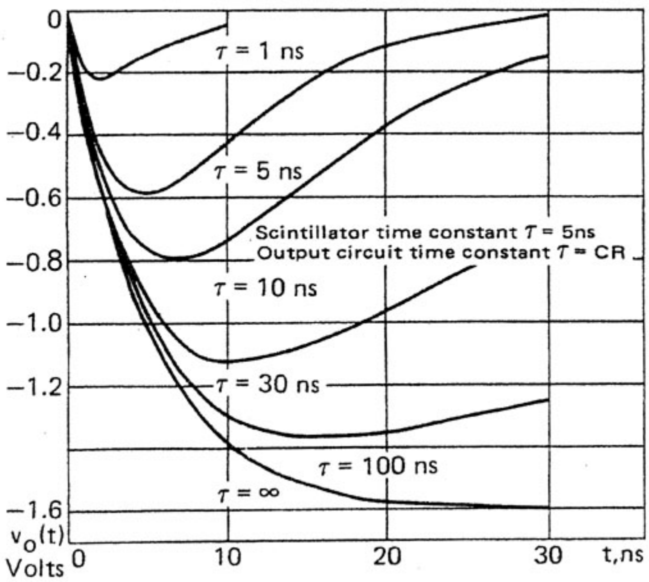

figure 2 output response curves for various time constants. The input excitation is a decaying exponential with a single time constant.

i) The maximum amplitude signal is obtained when $R \rightarrow \infty$. In this case the current I(t) is simply charging C and

$$V_o(t) = \frac{GNe}{C}[\exp(^-t/\tau_s)-1]$$

ii) The output voltage is a faithful reproduction of the input current i(t) only when $\tau << \tau_s$

iii) Consider the case $\tau = \tau_s$ =5 ns. When I(t) has decayed to within 1% of its intial value, $v_o(t)$ is still ~10% of ^{v}max. In other words, the output pulse has a long tail, which increase with τ.

iv) When R ≤100 Ω, implying $\tau << \tau_s$, the pulse is not integrated – this is designated "current mode operation" with the rise time of the cur rent and voltage pulses principally deter mined by the higher time constant. With $\tau << \tau_s$, the current pulse is integrated and the operation is now termed "voltage mode". Note how the rise time increases as "voltage mode" is approached and in the extreme case with $\tau \rightarrow \infty$, the voltage rise time is equal to the input decay time.

v) A long time constant τ is suitable for low event rates; if the rate ~I/τ , "pulse pile up" occurs (see Herbst, 1970 section 6.5).

vi When the photomultiplier is connected by matched coaxial cable of 50Ω impedance to an external ciruit, the peak voltage is ~100 mV, for the parameters previously assumed, compatible with the sensitivity of most commercial discriminators.

3 coupling capacitors

It is customary practice to earth the cathode and maintain the anode at an elevated potential. The signal output must be isolated by means of a good quality capacitor from the HV. Apart from the difficulty of obtaining non-inductive, low-leakage capacitors, there is the additional, unavoidable problem of pulse distortion. Consider the transmission of a pulse through the CR rentwork of **figure 3**,

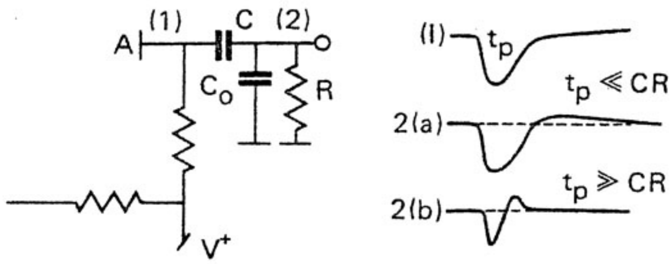

figure 3 pulse overshoot associated with CR networks

neglecting for the moment the effect of C_o. Although the output appears to be a faithful reproduction of the input pulse when CR<< t_p distortion free transmission is never possible: by choosing CR<< tp, quick recovery to the base line, but with overshoot, results; with CR>> tp a long recovery to zero with reduced overshoot obtains. Capacitance coupling thus causes the base line, or reference level, of the output signals to shift with rate and pulse amplitude. A long time constant, CR, is suitable for low event rates but for high variable rates, such a time constant gives excessive base-line shift. This form of distortion can be avoided by adopting the scheme shown in **figure 4** where the cathode is maintained at HV(minus) with the anode earthed or directly coupled to an external circuit. Interpreting the combined effect of C and C_o is clearly complicated in the general case because the equivalent circuit is characterised by three time constants and the output response is sensitive to rate – as manifested in base line shift and pile up.

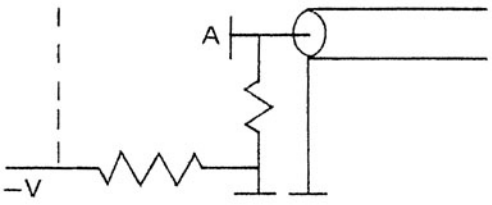

figure 4 DC anode coupling

4 signal splitting

In many applications, both energy and timing information is required on each event and hence two separate signals need to be derived from the photomultiplier. There are several possible ways in which this can be done.

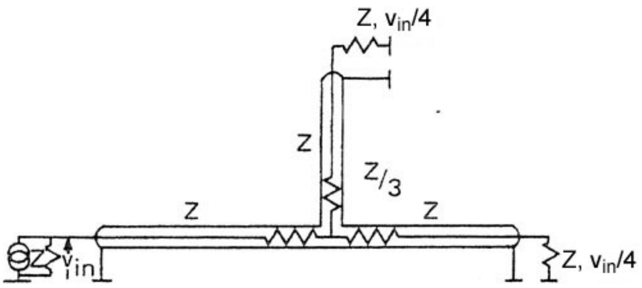

figure 5 reflection free splitting at the anode signal using transmission lines

Anode signal splitting, **figure 5.** This appears to be ideal since matching is maintained with $v_{out} = v_{in}/4$. However, the method is not widely used, possible because of the fact that the outputs are unavoidably coupled. The input impedance of an electronic circuit with active components invariable changes on overload resulting in poor matching on large signals.

Derive one signal from the anode and the other from the last or penultimate dynode as shown in **figure 6**. The signal is reduced in magnitude and opposite in phase with respect to the anode signal. The use of 50Ω coaxial cable ensures that the two outputs are very nearly independent since the coupling due to stray capacitance C_S is negligible in this instance. This does not apply in those applications calling for anode and dynode load resistance of say 100k and it may be preferable to use an earlier dynode output.

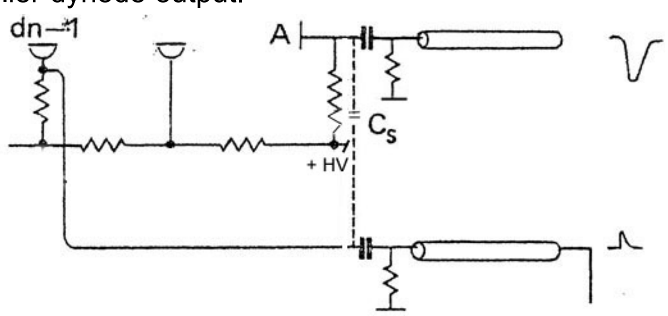

figure 6 method of deriving two signals from the same photomultiplier - C_S stray capacitance

Transmission line transformers in the form of coaxial cable wound around a ferrite doughnut. Although wideband operation is possible, the same problems of isolation mentioned are present.

5 signal amplification and impedance transformation

5.1 **preamplifiers** – the use of a preamplifier must be considered in those applications where the photomultiplier is separated from the data acquisition system by many metres of cable. Unless properly terminated, the transmission cable will introduce pulse distortion and reflections into the system. Charge sensitive preamplifiers perform the function of charge-to-voltage-conversion, while providing a low impedance output suitable for driving long cables. They are often used in conjunction with a shaping or main amplifier and the option of a preamplifier incorporated into a tube base is offered by several manufacturers.

The difficulties associated with fast photomultiplier pulses, where current saturation is a very real problem, have now been considerably reduced by the introduction of high speed pulse amplifiers in integrated or hybrid form. Their compact construction allows for convenient location close-up to the anode of the photomultipier. The essential characteristics of some of the above mentioned preamplifiers are given in **table 2**.

5.2 **amplifiers** (ac compensated). The word amplifier may be prefaced by main, linear, research, spectroscopy or timing filter, to indicate the intended purpose of the instrument. These amplifiers provide high gain (typically 500 – 2000) with good signal to noise ratio. Noise figures of 5µV (referred to the input) at full gain are achieved by limiting the bandwidth to about 5 MHz by the internal, selectable shaping time constants. Compensation techniques such as 'pole-zero cancellation' and 'base line restoration' are standard features which help to minimise pile up and base line shift with rate. The shaped output pulse delivered by the amplifiers may usually be fed directly into an instrument performing pulse height analysis, such as single or multichannel analyser.

5.3 **dc amplifiers** (uncompensated). These have no ac compensating circuits, except to balance out small inductive elements in the wiring. They are characterised by fast rise and fall times of 1 – 2 ns, with low gain 1 – 10 typically, but units may be coupled together to provide an overall gain of ~1000. However, base line shift with temperature (but not rate) is a serious limitation. The LRS, 12-channel photomultiplier amplifier (Model 612), for example, has an outstanding performance: this amplifier provides a gain of 10 per channel, with an output dc offset coefficient of only 50µV/°C; this is important where a subsequent instrument measures pulse amplitude from a zero level. The 200 MHz bandwidth is obtained at the expense of noise as reflected in the figure of 50µV (referred to the input) at 10X gain. **Figure 2** (drawn for 100 photoelectrons) indicates that the noise figure of 50µV is still neglibible even for single photoelectron signals.

An important feature of any amplifier is undoubtedly the retention of energy information during the amplification process and all of the amplifiers mentioned so far do this but in different ways. The ac compensated amplifiers, primarily designed for gamma ray spectroscopy and related applications where rates are moderate, do not reproduce the original pulse waveform. The dc, uncompensated amplifiers provide gain while retaining the shape and time information of the input signal. They find application in fast pulse instrumentation where their use in conjunction with fast gates permits analysis decision making in a matter of nanoseconds.

It is not immediately obvious why additional amplification of a photomultiplier signal should be necessary when the device itself can provide a gain in the region of 10^7 – 10^8. Frequently, it is the impedance transformation and matching properties of the amplifier that are utilised rather than the gain it provides. The need for such an amplifier depends on three factors: the nature of the output signal (shape, amplitude); the analysis to be done on the pulse (area, height or shape measurement) and, thirdly, the input signal specifications of the electronic instruments under construction. An amplifier or preamplifier may therefore serve as a vital link between the photomultiplier and the data acquisition system, especially when the output pulse is too fast to allow direct input to an inherently slow electronics system.

6 pulse height measurements

Pulse height distributions can be measure in several different ways. The various methods available together with some of the considerations covered in the previous section may be illustrated by recourse to a particular problem in nuclear physics, the measurement of a beta spectrum using a plastic scintillation counter. Assuming 700 photoelectrons per MeV, (see **table 1**), a photomultiplier with G = 10^6 and t_p, = 2ns (fwhm) will generate an anode

$$\text{current ia} \approx \frac{eNG}{t_p} \approx 5mA$$

Linear operation to better than 1% is unlikely at such high current levels with standard venetian blind photomultipliers, (see, for example, “Space charge effects, transit time spread and output circuits”, by A.J. Parsons) and it is therefore, advisable to reduce G to 10^5 and restore the overall gain by using a preamplifier if necessary. The Ortec 276, for example, provides a conversion gain of ~0.1V/MeV for this scintillators with, G = 10^5. Following the discussion given previously (2, part iv) the rise time of the pulse cannot be much more than ~20ns, even in the ‘voltage mode’.

One may wish to display the energy spectrum using a commercial multichannel analyser (MCA) but it is vital that the input signal requirements of the actual MCA to be used are first carefully studied. MCA’s fall into two main categories: those that have a charge sensitive input and may be connected director the photomultiplier (LeCroy qVT 3001 and Tracor Northern TN 1705, for example) and those that only accept a shaped tail pulse of rise time > 0.1µs from a preamplifier (Nuclear Data ND 1200 and Canberra Omega One, for example). Analysers of the first type have their input sensitivity specified in picocoulombs (e.g. 0.25 pC/Channel, 256 pC full scale) while those in the second category work in the range 0-10 volts, typically.

Pulse height information may also be obtained by using a single channel analyser (SCA). Although data acquisition takes much longer, compared with the use of an MCA, the final result should be the same. Again, the input signal requirements of any device used must be carefully studied. Most commercial units require a shaped input pulse with a minimum rise time restriction making the use of a preamplifier – amplifier combination almost mandatory. Timing SCA’s combining the two functions of single channel, pulse-height analysers and pulse timing in one unit.

Integral discriminators are widely used for the measurement of pulse height information. These also fall into two main categories:

i) those that are designed for use with shaping amplifiers (such as Ortec 421, Canberra 1432) have an input impedance of ~10k Ω and a sensitivity of typically 0.1 – 10V and

ii) those intended for direct coupling to the photomultiplier via a 50Ω matched line (these are discussed more fully in **section 7**).

A word of caution on the use of fast discriminators of type (ii) for the purpose of measuring energy distributions is necessary. These discriminators have been designed so as to optimize the time resolution – the actual signal energy at which the discriminator is activated is of secondary importance. The literature contains many examples of pulse height or 'energy distributions' obtained by varying the bias of an integral discriminator. Whether this is an acceptable procedure or not depends on the number of photoelectrons constituting the pulse. The current waveforms derived by Monte Carlo methods by Hyman et al (1964) bear this out. Anode current waveforms for a conventional fast photomultiplier with dynode secondary emission coefficients of typically 4 – 5 are shown in **figure 7**, for N = 10 and N = 100 photoelectrons. The striking feature of the waveform in (a) is the irregular shape and the appearance of multiple peaks, which could obviously give rise to repeated triggering from the same event. The fundamental information carried by a pulse is its area because this relates directly to the number of photoelectrons; integrating the pulse on a capacitor produces a voltage proportional to the energy. Therefore, measurements made with a discriminator may be interpreted as an energy distribution only under certain conditions. If the number of photoelectrons is large, say >100, the pulse shape is statistically well defined and N and v_{max} are directly related: if N<100 the energy distribution may be unreliable unless an adequate degree of integration is first performed in say a charge sensitive preamplifier – amplifier combination. These arguments apply, but to a lesser extent, to

i) photomultipliers employing a first dynode with high secondary emission coefficient
ii) photomultipliers with a venetian blind structure.

for instance, GaP has a secondary emission coefficient of about 30 – 40 which implies far less statistical variance in the shape of the current waveforms. Transit time spread in venetian blind tubes (10 – 40 ns depending on the tube type) provides a certain degree of regularization by smoothing the waveforms of **figure 7**.

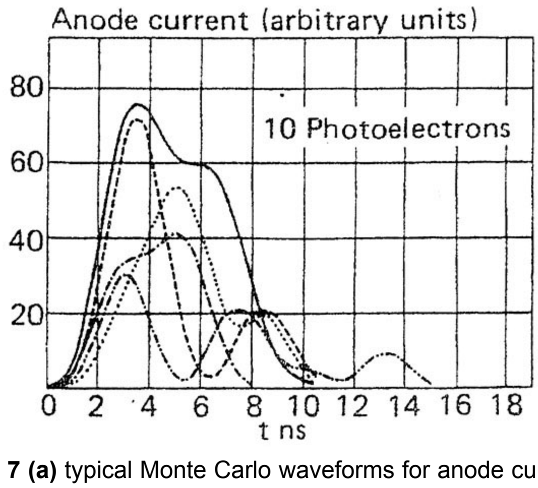

figure 7 (a) typical Monte Carlo waveforms for anode current taken from Hyman et al (1964)

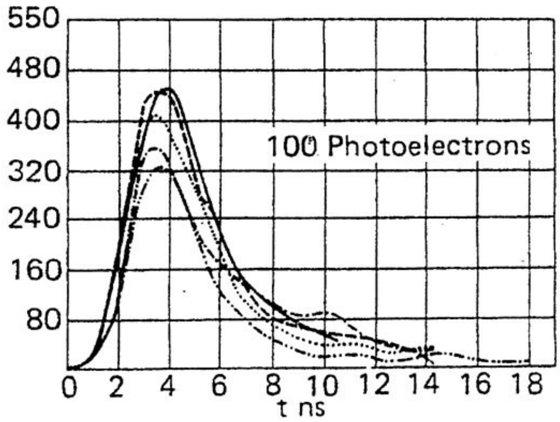

figure 7(b) typical Monte Carlo waveforms for anode current taken from Hyman et al (1964)

7 optimum time resolution

Precise information on the time of initiation of an event is of prime importance in certain experiments e.g time of flight measurements and nuclear lifetime determinations.

Post and Schiff (1950) showed by rather simply analysis that, for a system exhibition exponential decay in its light output, the time of arrival of the n th photoelectron is subject to a standard deviation of

$$\frac{\tau}{N}\sqrt{n}.$$

This formula predicts for a total charge Ne that the best resolution is obtained if the least possible charge is required to activate the discriminator. Gatti and Svelto (1959) and Hyman et al (1964), took account of the resolution of the photomultiplier and the nature of the discriminator, to arrive at the broad prediction that optimum resolution obtains when a fraction of about 10-20% of N is required to trigger the discriminator. These authors introduced five categories to describe the principle of operation of various discriminators.

i) straight response – current first exceeds threshold h.
ii) integral of straight response.
iii) straight response driving RC network.
iv) delay line clipping.
v) centroid of pulse by zero crossing.

Comparison with experiment shows good agreement for the relationship between the resolution and the fractional triggering level for categories i, ii and v (see, for example, Hyman et al fig. 17). Bertolini et al (1966) and Nutt et al (1971) have investigated i and v experimentally.

Several different types of discriminator are currently available and selecting the appropriate instrument for the particular application in mind could result in a considerable saving in cost. Naturally cost and performance are related but many applications do not demand a high performance discriminator. The terms ‘walk’ and ‘jitter’ enter into the specification of most instruments; these terms are explained in **figure 8**.

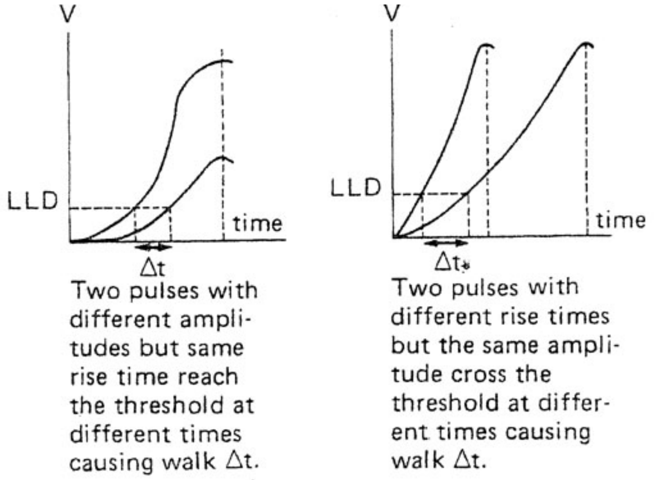

figure 8(a) explanation of the terms “walk” and “jitter”

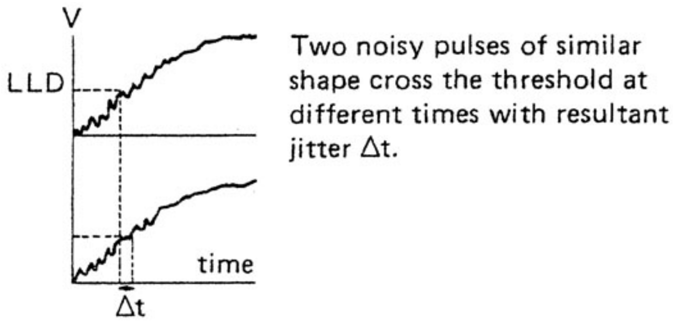

figure 8(b) explanation of the terms “walk” and “jitter”

i) Leading edge. The operation of earlier instruments was invariably based on the fast switching characteristic of a tunnel diode. This is a current switching element requiring a current pulse to switch state. Typical sensitivities of 50mV (1mA into 50Ω) are available but some, such as the Elscint FAD-N-1/2 which includes a fast amplifier, offer a sensitivity of 40µA. Discriminators working on this principle are now very easily and cheaply constructed by using fast voltage comparators, such as the advanced Microdevice AM 685. Leading edge discriminators exhibit excessive walk when pulses of large dynamic range are analysed.

ii) Zero Cross detectors. The time at which the diferentiated form of the input pulse crosses the zero axis is invariant with amplitude, for ideal pulses. The principle is illustrated in **figure 9**.

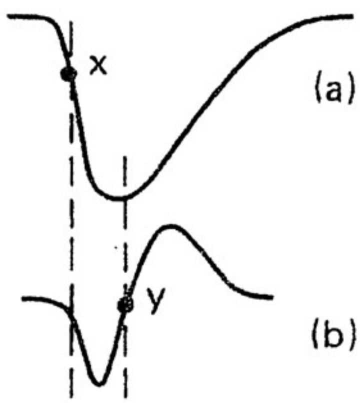

figure 9 waveforms of a) leading edge and b) zero cross timing

However, as pointed out by Bell (1966) the ultimate time resolution is determined by statistical (i.e. the total charge in the pulse) rather than systematic factors and the transit time spread of the photomultiplier degrades the resolution offered by this method. Zero cross timing generally gives poorer performance than the leading edge method with a large range of pulse sizes and shapes.

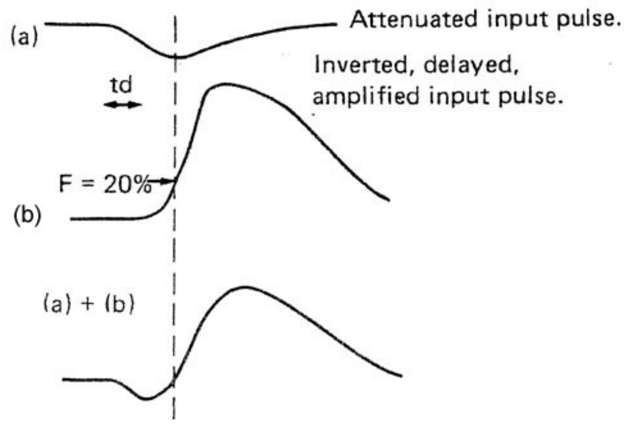

figure 10

iii) Constant fraction of pulse height. **Figure 10** illustrates the priciple of operation. Note that zero crossing does not take place at the peak amplitude but at a fraction of ~20% on the rising edge. Constant fraction discriminators offer superior performance compared with leading edge discriminators when the dynamic range is large. The systematic walk is zero only for signals that exhibit a constant shape.

iv) Snap-off timing – this is a further refinement of the constant fraction method and a discriminator of this type has been described by Arbel (1974). Here the charge storage properties of a snap-off diode are utilised to define more precisely themoment of zero crossing. In this case charge and not current is compared with a reference and thus the fluctuating signal current is integrated over a fixed period.

An attempt has been made in **table 3** to compare the performance of the various types of discriminator. This is difficult because of the wide variety of experimental conditions. However, most measurements listed in **table 3** appear to have been made under roughly similar conditions and probably establish the correct order of merit for the various discriminators. This data gives an indication of optimum performance when fast tubes are employed. The typical user of photomultipliers seldom requires this degree of time resolution and is better advised to employ a slower discriminator of the type mentioned in section 6, which, apart from being less expensive, incorporates charge integration as well.

8 conclusions

The fact that a photomultiplier produces a charge pulse at the anode when excited with optical radiation at the cathode, cannot be overstressed. Problems arise in many instances because this pulse is too fast for conventional electronic circuits or deriving a slow voltage pulse by integration: the degree of correlation however, between the voltage and charge pulses depends ultimately on the magnitude of N and the integration time. It is all too easy to connect together a selection of NIM units to obtain a set of results of doubtful value; to end up measuring something other than was intended.

table 1

Material	Decay Line (ns)	Efficiency eV/photon	Efficiency eV/electron	Number of Photoelectrons MeV^{-1}
Anthracene	29.3	65	500*	2×10^3
NaI(Tl)	230	30	250*	4×10^3
Stilbene	4.9	105	1200*	800
Liquids NE 211-2 13	2.3-3.6	200	1500*	700
Plastics Pilot 8-NE103	1.7-11.3	150	1500*	700
Cerenkov	~1	$5\text{-}10 \times 10^3$	$5\text{-}10 \times 10^4$	10-20†

table 1 – Summary of the properties of various scintillators
* Measured by Sharpe and Thomson (1958) for S11 photocathode
† for relativistic particles in medium with $\mu = 1.3$ (Meiling and Stary (1968)).
The figure given for the expected number of photoelectrons must be regarded only as a guide, since the wavelength of the light, the type of photocathode (the quantum yield) and the collection efficiency all bear on the final result.

table 2 **preamplifier characteristics**

Description/ Manufacturer	Gain	Z_{in}	$Z_{out}\Omega$	Signal Characteristics
Charge Sensitive Ortec 121	165mV/10^6 electrons	-	93	Tail pulse 50ns rise time
Integral Base Canberra 802-9	~33mV/pC	0.01μF in parallel with 200kΩ	93	Tail pulse 50ns rise time
Trans-Impedance EMI C501	~3.6V/mA	110Ω	2	4ns rise time
Fast operational amplifiers LRS VV100	10	1kΩ	25	2ns rise time
Voltage follower National Semiconductors LH 0063	1	$10^{11}\Omega$ in parallel with 8pF	1	1.6ns rise time

table 3

comparison of measured time resolution

Author	Mode	Source/ Phosphor	Dynamic Range	FWH (ns)
Whittaker (1966)	Zero Cross	14 MeV neutron NE 213 Pilot B	500:1	1.70
Wieber et al (1966)	Zero Cross + pedestal	Na^{22} Pilot B	100:1	-
Gedcke & McDonald (1968)	Leading Edge	NE 213	10:1	1.20
Nutt et al (1970)	Constant Fraction	NaI, Naton 136 Co^{60}	20:1	1.22
Sinai (1972)	Snap-off	NE 102 A, Na^{22}	100:1	0.36
	Constant Fraction	NE 102 A, Na^{22}	100:1	0.48
	Snap-off	NaI, NE 102A	20:1	0.91
	Constant Fraction	NaI, NE 102A	20:1	1.22

references

[1] J. Sharpe and E.E. Thomson, Photomultiplier tubes and scintillation counters, Electron Tubes Document R/P002 (1958)
[2] W. Meiling and F. Stary, Nanosecond pulse technique (Gordon and Breach, 1968)
[3] L.J. Herbst, Electronics for nuclear pulse analysis, OUP, 1970. See article by A.B. Gillespie – Nuclear pulse amplifiers
[4] R.F. Post and L. Schiff (1950), Phys, Rev. *80*, 1113
[5] E. Gatti and V. Svelto (1959), Nucl. Instr. and Meths. *4*, 189
[6] L.G. Hyman et al (1964), Rev. Sci. Inst. *35*, 119
[7] G. Bertolini et al (1966), IEEE Trans. NS, *13*, 119
[8] R.E. Bell (1966), Nucl. Instr. and Meths. *42*, 211
[9] J.K. Whittaker (1966), IEEE Trans NS, *13*, 399
[10] R. Nutt et al (1971), IEEE Trans NS, *17*, 299
[11] A. Arbel et al (1974), IEEE Trans NS, *21*, 3
[12] D.L. Weiber and H.W. Lefevre (1966), IEEE Trans NS, *13*, 406
[13] R. Sinai ideas in nuclear instrumentation. Elscint Ltd. 1972
[14] D.A. Gedcke and W.J. McDonald (1968) Nucl. Instr. and Meths. *58*, 253

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