Getting the best out of photomultiplier detectors

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Photomultipliers (the devices are often abbreviated to PMT) convert light into an electrical signal; they are available in numerous configurations and unsurpassed in their versatility and in many instances in their sensitivity. Despite being devices requiring an evacuated enclosure, i.e. they are not solid-state devices, they are still widely used when high speed photon counting is required. Photomultipliers consists of a photocathode, where photons are converted into electrons, making use of the photoelectric effect), a multiplier chain (strings of successive electron absorbers with enhanced secondary emission, called dynodes, the entire string using electric fields to accelerate electrons), and an anode, which collects the resulting charge or current. PMTs vary in speed and linearity of response, in the time fluctuations of the signal, in amplification factor i.e. gain, in the wavelength spectrum accepted, etc. The photocathode is typically held at a potential of -500 to -2000 volts relative to the anode. The photoelectron is accelerated towards a series of additional electrodes called dynodes. These electrodes are each maintained at successively less negative potentials. Additional electrons are generated at each dynode. This cascading effect creates 10^5 to 10^7 electrons for each photoelectron that is ejected from the photocathode. The output signal is collected at an anode maintained at ground potential. The principle advantage of a PMT is that it provides almost noiseless amplification of light signals – but remember that light consists of quanta and hence Poisson noise is inevitable.

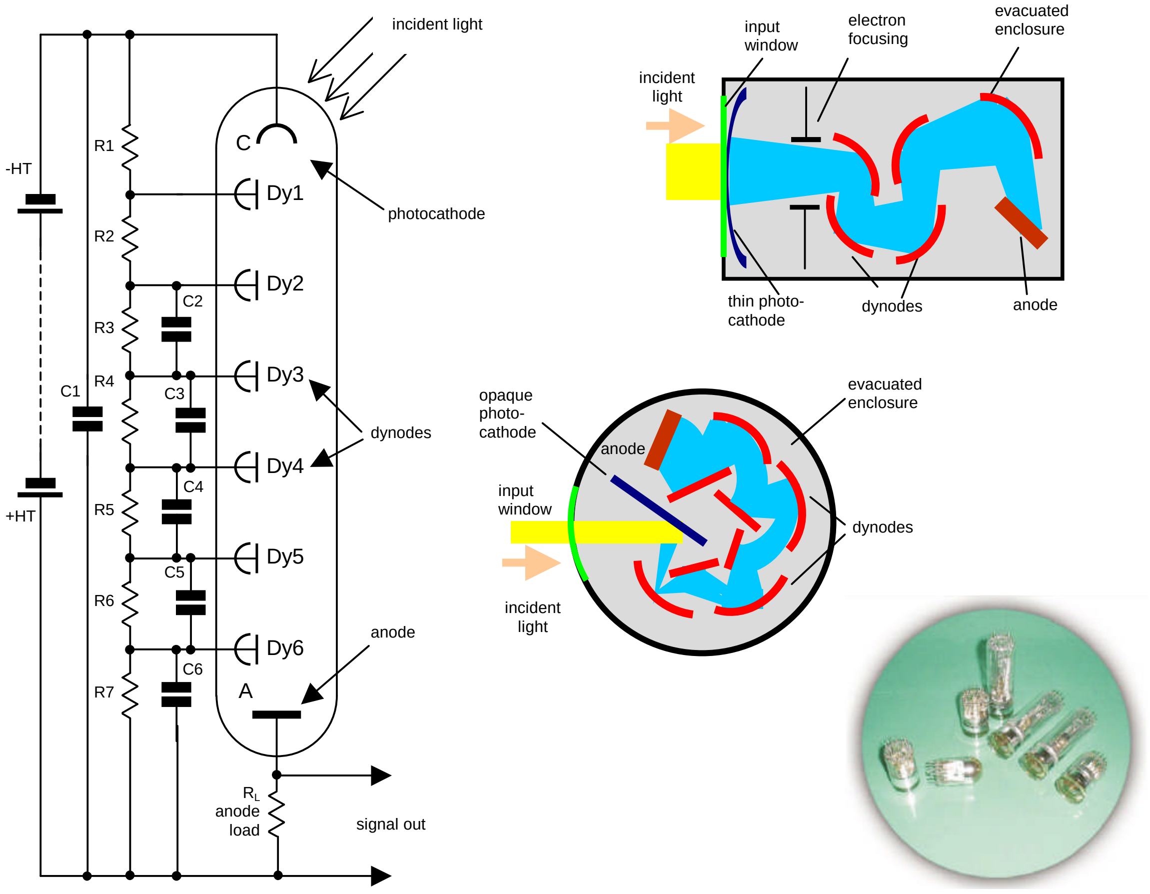

Figure 1: The basic photomultiplier electrical circuit (left) and examples of an end-on tube (top right) and a side-on tube circuit cathode (middle right). The image on the bottom left shows different types of tubes.

Photomultipliers are characterised by the quantum efficiency of the photocathode, by the spectral response of the photocathode, by the number of stages (i.e. dynodes) and by the response time of the output following an optical input pulse. The reader is referred to the many excellent application notes available from PMT manufacturers (Thorn-EMI, Hamamatsu Photonics, Burle etc.) and only the more unusual ways of using these devices is presented here. It is particularly important to follow the manufacturer's recommendations in connection with the voltage distribution across the dynodes, as determined by resistors R1-R7 in the example of Figure 1. Tubes are commonly specified in terms of radiant sensitivity, R (i.e. current obtained at the output for a given input optical power). Very often, particularly when the tubes are used in applications where photon counts need to be determined, the quantum efficiency needs to be evaluated. A useful and approximate relation between QE and R is given by:

QE (in %) = (124 / λ). R (measured in mA/W).

In general, PMTs are superior in detecting light in the UV/blue end of the optical spectrum rather than in the red / NIR region, although newer photocathode materials are constantly being developed to extend the response towards higher wavelengths. In the last ten years or so, different dynode structures and envelope materials and miniaturisation have resulted in extremely small and fast devices, such as those available from Hamamatsu (Figure 2).

When using such devices, it is essential to use construction and signal handling techniques appropriate to the frequency components present in the short pulses, i.e. suitable radio-frequency or microwave techniques capable of handling bandwidths extending to beyond 500-1000 MHz. While most more conventional tubes are capable of rise and fall times in the region of 2-5 ns (a typical FWHM is of the order of 5 ns), by increasing the interdynode voltage, and hence decreasing the photoelectron transit time spread, even 'old' tubes can be made to operate very fast if a few 'tricks' are put into place. Decoupling capacitors (C1-C6 in Figure1) are crucial, and low inductance ceramic units should be used, preferably arranged in a 'stripline' configuration as close as possible to the tube pins. If you are feeling brave, removal of the octal base of a side-on tube of the ubiquitous '1P28' variety decreases series inductance considerably and sub-nanosecond response are relatively easily achieved. For example, we have used similar arrangements to those described by Beck in 1976 to monitor Čerenkov radiation pulses that reflect the time profile of 1.5 ns high energy electron pulses produced by our Van de Graaff accelerator. The 'pulse' is shown in figure 3.

Although most PMTs are designed to produce relatively low maximum DC currents, usually in the range of 10-100 µA, more complex circuit arrangements can be used to coax them into producing much larger currents, up to several mA or even tens of mA. It should be stressed that any such modifications are approached carefully, and that the output linearity should be carefully checked.

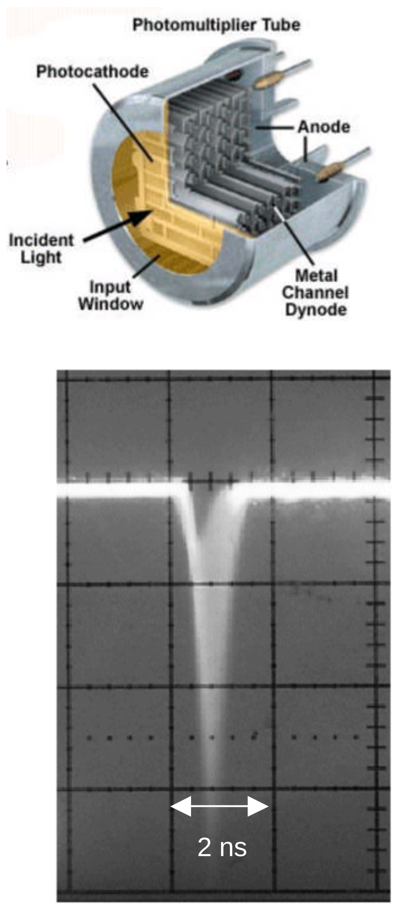

Figure 2: A miniature metal dynode tube and its time response to single-photon events.

In general, and irrespective of the performance of the tube, any attempt to generate high output currents is hampered by the fact that the current through the dynode chain must be made much higher than the output current if the interdynode voltages are to be maintained constant. Clearly using a high voltage power supply producing in excess of 100 mA to the dynode chain is rather impractical and a better way is to provide an 'active' dynode chain, such as that shown in Figure 4. Such an arrangement has been in use on our pulse radiolysis facility for many years.

The basic idea (originally suggested by Prof. B.D. Michael) is to use an emitter-follower chain to buffer the dynode: the output impedance at the transistor emitters is very low, particularly if multiple emitter followers are used. High value voltage setting resistors can thus be used and moreover can be made variable, so that optimum dynode voltages can be 'tweaked' for the particular tube in use.

Figure 3: A successful attempt to produce an ultra-fast PMT detector at low cost.

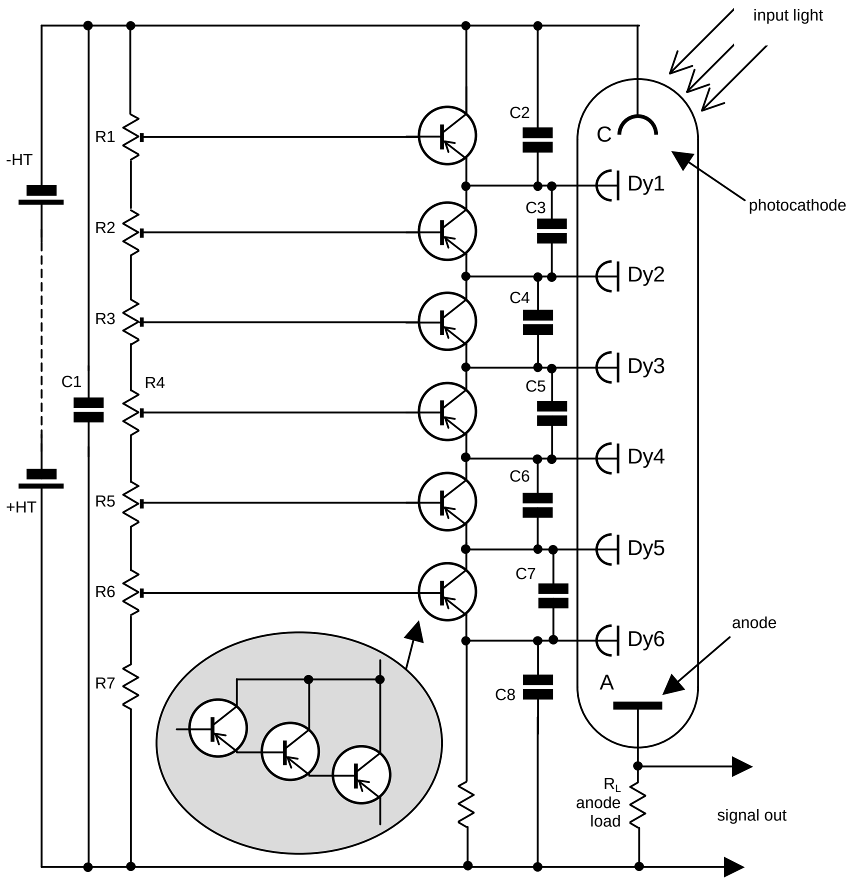

Figure 4: An active dynode chain is used around the photomultiplier to minimise the bleed current through it and hence reducing the HT current requirement from the power supply. High voltage cascaded PNP devices (MPSA92 or 2N5416) are used to buffer the outputs from a chain of preset resistors (each 1 MΩ). Capacitors C2-C8 (10 nF) should be fitted all along the chain and should be of equal value to minimise excessively high transient voltages across the transistors.

If adjusted carefully, this type of arrangement can produce in excess of 5 mA for short periods (10's of ms), with side-on tubes and within the constraints of photocathode 'fatigue', described later. It is possible to generate currents of 25-35 mA, albeit for short periods (0.1 –1 ms) by using a slightly different approach. The usual operating mode of the tube is to collect photoelectrons at the anode, or in cases where a lower gain is required, at some previous dynode, which is electrically tied to the anode and subsequent dynodes. However, when high currents are required, it is advantageous to monitor photoelectron loss at a given dynode while subsequent dynodes are biased to increasingly positive voltages. This arrangement, originally proposed by Ellison and Wilkinson in 1972, is shown in Figure 5. The ‘main’ negative power supply has to provide a moderate current, while the lower voltage positive supply must be capable of supplying the high output current, and subsequent dynode current. Although an active chain can be combined with this circuit, lower value (10-100’s KΩ) chain resistors can be used with larger than usual decoupling capacitors (C1-8). Values of up to 1 μF are OK but smaller, high frequency capacitors should be placed in parallel.

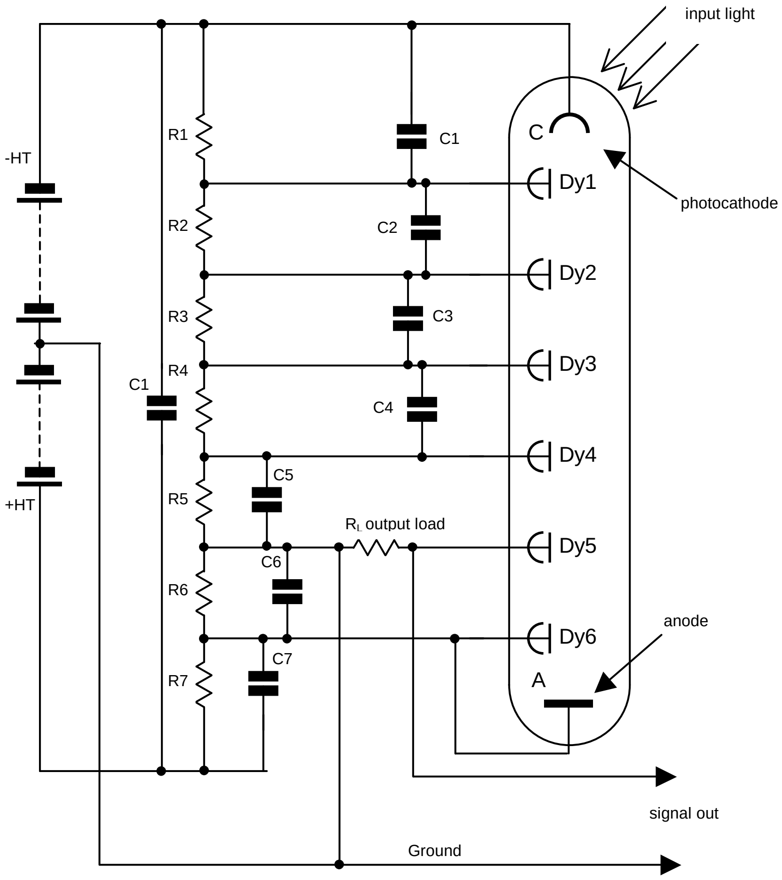

Figure 5: A dual supply, high current dynode chain, where output photocurrent results from loss of electrons at an intermediate dynode.

It is emphasised that the linearity of such arrangements must be checked periodically due to ‘ageing’ of the cathode and dynodes. The linearity can be most readily monitored by illuminating the tube with two light sources: the variable steady-state or long-pulse light that the tube is to be used with and a much lower, constant amplitude short light pulse, provided by an LED. By AC coupling the tube output the amplitude of the short pulse can be determined as a function of the tube output: if the arrangement performs linearly, the short pulse amplitude will remain constant throughout the range.

It should be noted that ‘peculiar’ results are not unusual and that although in general one would expect saturation to set in at high currents, supra-linear response can be obtained in some cases. This apparently ‘odd’ behaviour is easily explained: at high output currents, it is the last dynode which supplies most of it and hence the last dynode-ground voltage is reduced. Since the high voltage supply is, in general, well stabilised, an increased voltage is presented to all the other dynodes; early interdynode voltages are thus higher and the resulting gain is increased.. As a general rule, it is inadvisable to make use of the very convenient property of PMTs: gain setting by HT voltage adjustment; while the photocathode is in general very linear indeed, it is very unlikely that acceptable linearity can be obtained over a range of HT voltages. A simple solution is to replace the bottom dynode chain resistor with an appropriately rated zener diode. This will stabilise the gain and eliminate the supra-linear response, but not of course saturation at high output currents. Careful experimentation and voltage adjustment is always worthwhile. But then again, the tubes were never intended by the manufacturers to operate in such regimes!

It is worth noting why high output currents are sometimes required. They are most useful when some form of transient absorption measurement is required e.g. in pulse radiolysis and flash photolysis work. The signal-to-noise ratio in photomultiplier detector can be calculated from square root of the number of photoelectrons, N, in a given integration period, τ, due to the flow of cathode current i_c.

This is outlined below:

Number of noise photoelectrons = $(i_c\ \tau/e)^{1/2}$. e = electronic charge (1.6 x 10^{-19} Coulombs)
Number of 'signal' photoelectrons = $i_c\ \tau/e$ and hence the signal/noise ratio = $(\pi i_c\ \tau/e)^{1/2}$

Thus, to double the signal/noise ratio, the analysing light must be increased by a factor of four. In order to observe an absorption change K, with a given signal to noise ratio SN_{obs}, the minimum photocurrent i_c must be :

$i_c = (e/\pi\ \tau)(SN_{obs}\ /K)^2$ or $\tau = (e/\pi\ i_c)\ (SN_{obs}\ /K)^2$

A reasonable practical upper limit to photocurrent with a conventional circuit arrangement is around 50 μA. For a SN_{obs} of 10:1, the minimum observable absorption change K and observation time, τ, are thus approximately related by:

$\tau = 10^{-13}/K^2$ i.e. i.e. $K = 10^{-2}$ with a time resolution of 1 ns,
$K = 3 \times 10^{-4}$ with a time resolution of 1 μs,
$K = 10^{-5}$ with a time resolution of 1 ms.

This is just another way of saying that if we need to observe small absorptions at short times, the only way out, other than the use of e.g. signal averaging techniques, is to increase the input light intensity and the output current. If we do that however, the detector is unlikely to perform well at long times. This is due to the phenomenon of photocathode 'fatigue'. When an energised tube is in the dark, a very small 'dark' current is produced, typically a few nanoamps or less. If it is then illuminated with a step function, the initial 'full' sensitivity is realised and a given output current is produced. After a few tens of milliseconds, the output current is observed to decrease, following approximately exponential kinetics, eventually settling to a new steady-state level, typically around a few percent or so lower than the initial value. The exact drop in sensitivity is a function of both the input light intensity falling on the photocathode and of the output current. The former is due to heating of the photocathode, while the latter is generally considered to be the result of dynode heating. At low light levels, this phenomenon is negligible, but at high levels, particularly when a low number of multiplying stages is used, the effect can be very prominent and can lead to loss of sensitivity of 30-50%. Most often, side-entry tubes suffer less from fatigue, as a result of the more massive, opaque photocathode. Again, experimentation and selection of tubes is the only practical manner to minimise this effect. Less problematic is the recovery from illumination, when the dark current does not return to the initial lo value immediately following removal of illumination.

However, in applications where low light levels are to be sensed, and in particular where photon counting methods are used, it is important to minimise as much as possible the extent to which a tube is exposed to light. In extreme cases, where a tube has been overloaded, it may take several days for the dark count rate to be restored. The use of shutters, gated or ramped supplies should be considered when the ultimate performance is required. While the previous descriptions have dealt with measurements of high light intensities, a photomultiplier is really best at detecting single-photon events; after all that is region where they are designed to work! Manufacturer's recommendations should always be followed, but it is still a good idea to experiment with the particular tube in use. For example, the output pulse rise and fall times are often dependent on the area of photocathode illuminated, and on the position of the photocathode which is illuminated. In general, 'side-on' tube are worse in this respect than end-on tubes, and small tubes are often preferred. Common sources of 'trouble' are stray magnetic fields from motors, transformers etc. which shows up as poor pulse-to-pulse reproducibility and often ‘inexplicable’ jitter. Of course, there is nothing inexplicable about such phenomena when elementary physics is considered: electrons are charged particles that are easily deflected by even small magnetic fields. Cooling of the tube, or rather the photocathode, is an excellent way to decrease the dark count rate, though it is rather difficult to achieve in practice. Careful consideration must be given to atmospheric water vapour condensation on the input window, and indeed around high voltage connections. It is best to purchase complete assemblies rather than attempt a ‘home-brew’ solution. Red-sensitive tubes in particular will often benefit from even moderate cooling, since the photocathode material (multi-alkali) is noisier than that used in blue-sensitive tubes (bi-alkali). The recently introduced metal dynode tubes are hard to beat as a general-purpose photon counting detector when used in ultra-fast applications. They are small, rugged and provide sub-nanosecond performance without too much difficulty. Once again, it is best to operate them at high inter-dynode voltages to minimise photo-electron transit-time spread. Due consideration should be given to termination of the output electrode. In practice this really means working into a matched cable termination, almost exclusively 50 Ω. It is worth remembering that the tube output is essentially a perfect current source, i.e. the inherent output impedance is very high. Back-matching the output cable is often preferred: a 50 Ω resistor is placed directly at the tube output which also feeds a 50 Ω coaxial line, itself terminated by 50 Ω. An excellent pulse response can be obtained in this way, but of course the output voltage is halved. Although specialised tubes to provide 10’s of milliamps of pulse output current are available, the output of the metal dynode tubes should be restricted to around 100 μA or so. A resulting output voltage of 2.5 mV is therefore produced and some amplification is thus most often required. We tend to use very-wideband amplifiers with a high frequency cut-off of 500 MHz at least, usually configured as non-inverting stages. In photon counting applications, there is little need for a response down to DC and hence AC coupling of the amplifier is often quite acceptable. Very low cost systems can be assembled from microwave ‘pill’ amplifiers, such as those available from Mini Circuits: types ERA-1, ERA-2 and ERA-3 are particularly suitable. Small surface-mount capacitors of around 1 μF ensure an acceptably low LF roll-off and the whole arrangement can be easily and quickly assembled on a microstrip type of printed circuit board.

Finally a word about power supplies. At first sight, the gain of a PMT which has n stages should be equal to δ^n, where δ = multiplication or gain factor of each stage. However, δ is not a linear function of applied interelectrode voltage, primarily due to space charge effects. A more appropriate expression for the mean overall gain is:

$$G_n = f A V^n \exp[-n (V/V_{max})], \text{ where:}$$

f = efficiency of collection onto one dynode of all the electrons emitted from a previous dynode;

A= efficiency of secondary electron production from a given dynode;

V= voltage difference between dynode stages;

V_{max} = value of V where secondary emission is maximum;

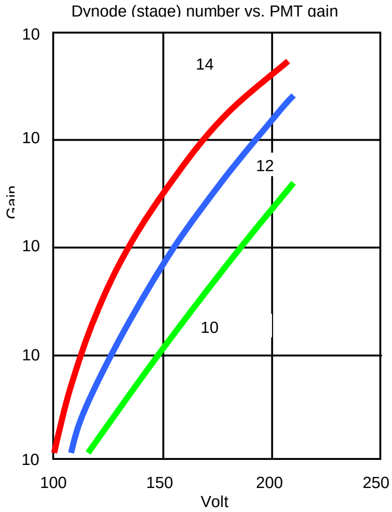

Figure 6: Typical variation of tube gain as a function of HT voltage.

A typical plot is shown in Figure 6. The take-home message is very simple: small variation in HT voltage = significant variation in gain. It is therefore essential not to be mean when specifying power supplies and to purchase units that are as stable as possible. The other consequence of this is that it is, in principle at least, relatively easy to modulate the gain of a PMT should that be required. In practice, modulation of the voltage applied to one of the early dynodes provides the greatest modulation depth for a given voltage. A phase detector is thus easily realised by AC coupling the reference waveform to the modulating dynode, generated from a suitable low output impedance amplifier. Phase detection at 10's of MHz is thus readily possible with simple RF amplifier modules, intended for the communications market. Again, however, experimentation with setting the optimum dynode bias voltage is necessary to achieve the maximum modulation depth: 50% or so is easy to achieve, 80-90% is hard: remember that the photoelectrons generated at the photocathode have to 'go' somewhere. For the same reason, it is not readily possible to achieve perfect gating with, say, a pulse amplifier. Long gating times (>1 μs) are of course more straightforward to achieve than shorter times: there will be a tendency, following the re-application of the operating dynode voltage, for any photocathode-generated space charge that has been prevented from further amplification, to appear as a charge burst. Nevertheless, a gating depth in excess of 50:1 is not only possible but very useful when the presence of intense unwanted output currents may overload any subsequent detection electronics. Very long gating periods, with high output currents can also be achieved; a very useful discussion appears in: "Signal linearity, gain stability and gating in photomultipliers: application to differential absorption lidars" by Bristow *et al*.

In conclusion, PMTs are extremely versatile devices used in the detection of light over a very large dynamic range. There are many more modes of operation other than those described here that are possible; this note is restricted to arrangements that we have experience with. The interested reader will doubtless have examined the extensive and excellent literature available from PMT manufacturers. With moderate care and patience, excellent performance can be obtained from these essentially very simple devices. It is definitely a good strategy to buy a beer every now and then for your local supplier representative; the reward is often a bunch of tubes labelled 'try me'! Finally, it is interesting to note that the most undesirable quality of PMTs, generation of shot and photon noise, is just what made them an early commercial success around the time of WW2: the principle market was supply of broadband, i.e. 'white' noise sources for purposes of jamming radar and other radio frequency communications! In those days, there was no other easy way to produce truly random noise. In comparison to modern digital pseudo-random sequence generators, the elegance and simplicity of using two evacuated glass envelopes, one a light bulb to produce a low number of photons, the other to detect them is really to be admired.

References:

Beck. G. (1976), Rev. Sci. Instr. **47,** 537-541

Ellison, D.H. and Wilkinson, F. (1972), Int. J. Radiat. Phys. Chem., **4**, 389-391

Bristow, M. P., Bundy, D. H. and Wright, A.G. (1995) Applied Optics, **34**, 21, 4437-4452

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