

technical reprint

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practical photon counting

1 introduction

Astronomers, in the early 1950s, were the first to use photomultipliers in the photon counting mode for measurements on stars of very low magnitude. Since then there has been a rapid increase in photon counting applications. Luminescence techniques are extensively used in clinical medical and drug testing and in the food industry inspecting for antibiotics, insecticides and bacteria. Laser scattering is used in Raman Spectroscopy for molecular analysis and in sub-micron particle sizing. These developments have been helped by improvements in photomultiplier performance and compactness and the advent of microelectronics and computers.

The power of the photon counting technique stems from the fundamental principle upon which it is based: electromagnetic radiation is quantised and so counting these quanta (photons) provides the best and most direct method of measuring the intensity of the radiation. Photomultipliers by virtue of their high gain and low noise are detectors ideally suited to providing a discrete pulse for each photon detected. Pulse height discrimination makes photon counting the least sensitive method to sources of noise other than thermionic emission. Additionally the output is presented in digital form ideally suited to processing by computer.

Setting up a photon counting system used to be complicated requiring voltage dividers, high voltage power supplies, photomultiplier housings, low noise amplifiers and fast discriminators. Today a fully integrated photon counting package, factory preset, and with bespoke software can be purchased and easily operated. However, it is still important to understand the essential elements of a photon counting system and their optimisation. This is especially true for those who want to assemble their own system.

2 instrumentation for photon counting

The elements of a basic photon counting system are shown in **figure 1**

The system can be assembled from stand-alone electronic modules or preferably it can be integrated into a single package. The following describes the function of the system in more detail.

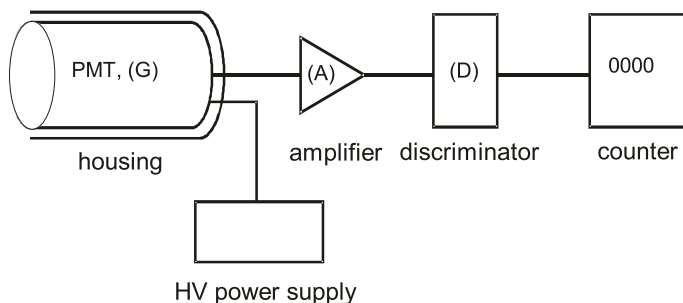


figure 1 the elements of a photon counting system.

The pmt window material and photocathode spectral response should be chosen to match the wavelength range of the radiation to be measured. The photocathode converts each detected photon into a photoelectron that is amplified by secondary emission at a series of dynodes held at progressively higher potentials. The gain (**G**) is a function of the number of dynodes and the overall voltage. Photon counting requires the pmt output pulse to trigger the discriminator (**D**).

A typical fast discriminator triggers at 50mV but this would require a pmt gain of 10^8 to 10^9 . Although such pmts are available the corresponding high voltages and current levels involved invariably cause instability and light feedback problems. In practice a fast, 50Ω input impedance electronic amplifier (**A**) of gain 100 shares part of the amplification process. A pmt with 10 or 11 dynodes operating at 10^6 to 10^7 gain is therefore more practical and thus commonplace.

To avoid electrical interference, the amplifier and discriminator are best integrated into one electronic module and should be connected to the pmt output by a short length of co-axial cable. In a lightdetector package we improve on this by connecting the electronics directly to the anode of the pmt. The pmt and electronics are installed in a screened housing (usually incorporating RF and magnetic shielding).

The operating voltage will typically be in the range 800 to 1500V, depending on the choice of pmt. How to determine the operating voltage will be covered in the next section. Suitable power supplies are available in a range of forms: laboratory benchtop units; rack mounting units; DC to DC converter modules; Cockcroft-Walton power bases and active voltage dividers. The power supply can be integrated with the housing or detector module.

Amplifier/ Discriminators are available with a choice of signal logic outputs - TTL, ECL. The logic output of the discriminator is connected to a counter. This can be a benchtop frequency counter, a board installed in a computer with accompanying analysis software, or a counter module with its own processor and computer interface. An important advantage of a counter with application software is that the user is guided through the setting up procedure.

Photodetector modules are also available with a USB interface and application software.

3 optimisation of a photon counting system

There are two parameters that must be optimised for photon counting: the discriminator setting and the pmt operating voltage.

Amplifier/Discriminators come in both fixed threshold and variable threshold versions. The former is optimised by the manufacturer and for most applications the flexibility of the latter is unnecessary. In practice a threshold of 2mV offers optimal performance. A lower threshold would render the counter susceptible to interference and a higher threshold would demand higher performance of the amplifier section, previously mentioned.

With regard to setting the operating voltage: in an integrated module this is usually set by the manufacturer. The following section refers to a system comprising discrete units.

4 performance characteristics of photomultipliers

To give a theoretical basis to the system we must consider the size distribution of pmt anode pulses, when viewing a source of single photons. This can be appreciated by looking at the anode pulses on an oscilloscope.

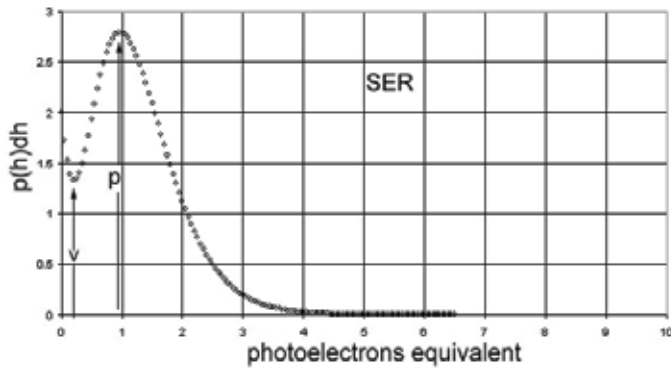


figure 2 the pulse height distribution of a photomultiplier in response to a low light level is called the Single Electron Response (SER).

The gain process in a pmt derives from secondary electron emission. It is a quantised process and ideally should obey Poisson statistics. Although all events start with a single photoelectron, the statistical nature of pmt gain means that the anode pulses will vary in magnitude from one pulse to another. That is, the gain is noisy and the degree of fluctuation is related to the mean gain of the first dynode (the higher the better). Inspection of the pulse height distribution reveals an excess of small pulses which depart from the Poisson distribution. These are the result of other physical processes, such as photoelectrons landing on the edge of d_1 .

The measured pulse height distribution is called the Single Electron Response (SER) of the pmt shown in **figure 2** and consists of a peak at p and a valley at v . One way to measure the SER is with a multichannel analyser. Since most of the signal lies to the right of v then v is a good place to set the threshold of the Amplifier/Discriminator as this is the most stable point on the entire distribution. Knowledge and understanding of the shape of the SER will help appreciate the significance of the plateau characteristic that will be discussed in section 5.

For a pmt with anode pulse width, t , the mean peak pulse voltage at the input of a 50Ω impedance Amplifier/Discriminator is: $\sim 50Ge/t$

$$v_o \sim 50 \times 10^7 \times 1.6 \times 10^{-19} / 5 \times 10^{-9} = 16mV.$$

As the pulse height is proportional to the gain the selection of G will determine the proportion of the anode pulse height distribution that will exceed the threshold voltage and hence the measured count rate. The gain is related to the HV by a relationship of the form $G = aV^m$, the value of m is about 8 for an 11 stage pmt and consequently G varies rapidly with V .

Starting at a low HV (**A** in **figure 3**), the SER has few pulses above the discriminator threshold. By increasing the HV to (**B**) about 5% of the pulses are now above the threshold. At (**C**) approximately 50% of pulses are above the threshold, and at (**D**) most are counted. Further increase in HV has little effect on the number of pulses counted. Note that because the light level is kept constant the areas under the curves of **figure 3** are the same.

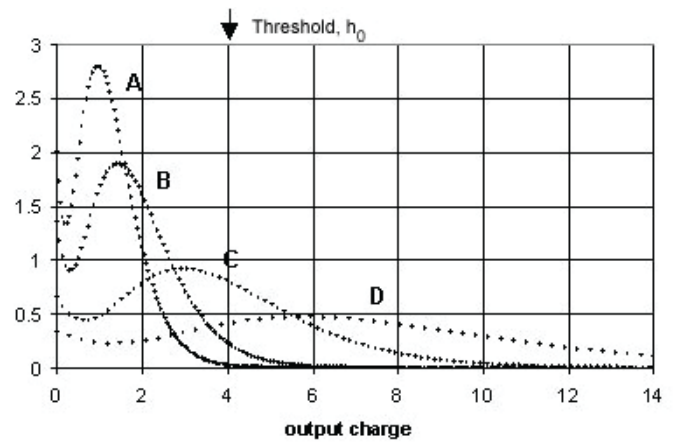


figure 3 SER pulse height distributions showing the effect of increasing the pmt operating voltage resulting in progressively larger output charge distributions from left to right. The areas under the curves are all equal.

A plateau curve is measured by noting the count rate for a series of HV settings, incremented by 25 volts. The resulting curve is shown in **figure 4**. This curve is known as a plateau characteristic because of the central flat region. The curve is often drawn using a logarithmic vertical scale for the count rate.

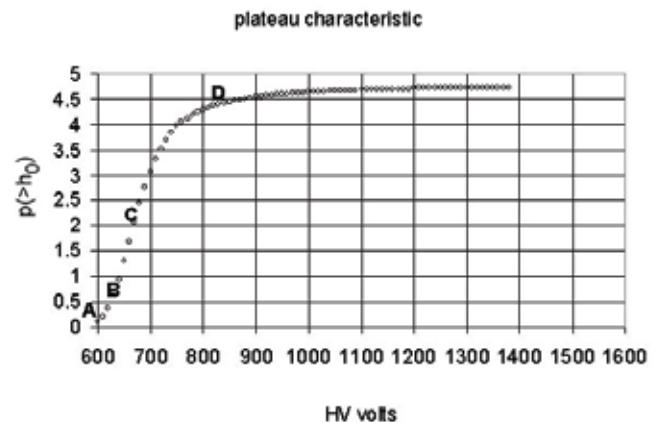


figure 4 the plateau characteristic is the count rate above a fixed threshold h_0 as a function of HV. A good photon counting pmt is one which attains a long, flat plateau as illustrated.

5 setting up procedure

When adjusting the pmt voltage take care not to exceed the voltage for the maximum rated gain, stated on the manufacturer's test ticket. The pmt may become unstable above this voltage leading to a permanent loss of performance. Note that the voltage given will be less than the maximum rated voltage for the pmt in the manufacturer's literature.

Start with the light source off and with the HV at 500V. Increase the HV in steps of 25V until there is sufficient gain at this HV setting (V_1) to produce greater than ~ 10 counts / second. This corresponds to region AB of **figure 4** for dark counts. Switch on the single photon light source and increase the intensity until the counts are about 100 times those of the dark count. With this light setting you can now measure your first plateau characteristic by starting some 100V lower than V_1 . It is instructive to plot a second plateau characteristic at 10 times the light level. The curves should have the same shape and this is a good check that the system is functioning correctly. Repeat measuring dark counts only.

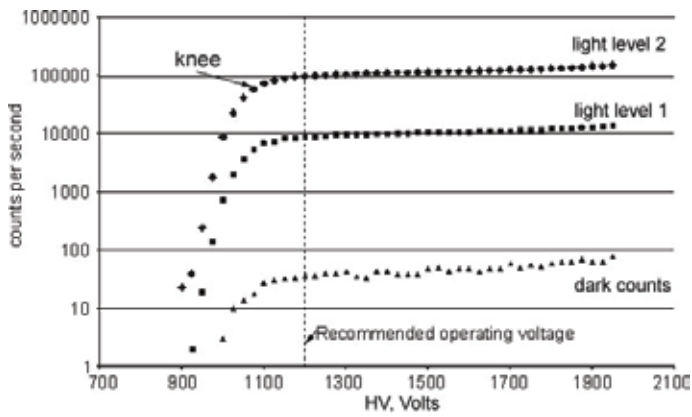


figure 5 the counting characteristics obtained from the setting up procedure described in section 5.

The point of turnover on the plateau characteristic is called the knee voltage and a sensible operating point is to the right of this but its actual location is a matter of choice. For repeatability and consistency we locate the operating point where the slope of the curve first reaches a critical value such as $0.2\%V^{-1}$. This is a sensible operating point because it ensures that the count rate is insensitive to changes in system sensitivity and also we are clearly counting most of the single electron pulses. A spreadsheet can be used to calculate the slope of the curve between the measured points. The best operating voltage will be above the knee voltage but further to the right, the plateau slope may be less but the dark count will be greater as can be seen from the dark count characteristic in **figure 5**. From our experience we find that setting the operating point to the knee voltage +100V is satisfactory.

An advantage that comes from buying a photon counting pmt that has been selected by ET Enterprises Ltd. for photon counting applications is that the test data supplied with the pmt includes the knee voltage (measured with calibrated test equipment). The user can compare his own results to the test data for confirmation of correct operation. Additional useful information includes the plateau slope, the dark count at the knee voltage and the dark count 100V above the knee voltage. Also, we have a wide range of housings and accessories to allow you to assemble a photon counting system with your choices guided by our technical staff. Full product details are available on our web site:
www.et-enterprises.com/pmt-accessories

6 the module approach

So far we have discussed the elements of a photon counting system. A system can either be assembled from stand-alone electronic modules providing the user with flexibility and choice of operating point, or purchased as a factory-set integrated package providing ease of use and invariably a more compact solution. ET Enterprises offers compact, low power consumption photon counting modules particularly suitable for use in portable hand-held instruments and for laboratory use. We can even supply a photodetector module designed specifically to be compatible with an existing instrument or one under development.

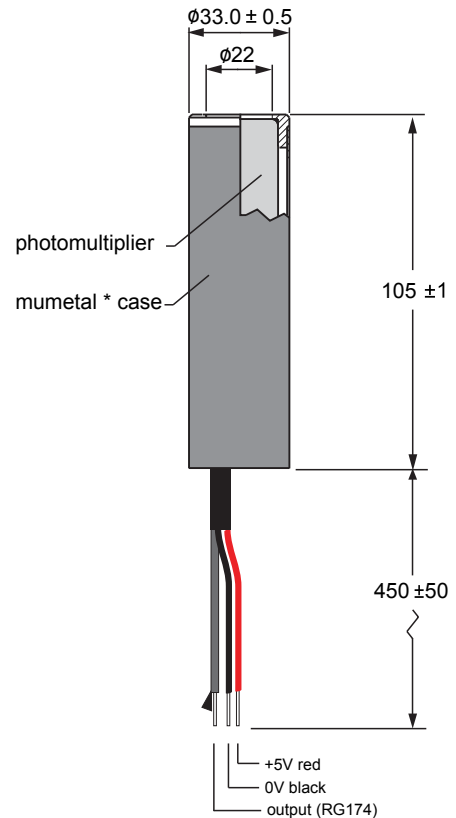


figure 6 An example of a photon counting module. It comprises a 9111B, 25mm diameter, fast, end window photomultiplier with blue-green sensitive bialkali photocathode, a +HV power supply, and high speed Amplifier/Discriminator all encapsulated within a cylindrical mu-metal case, providing a high level of immunity from the effects of external magnetic fields. Low voltage and TTL signal output connections are by axial flying leads.

7 conclusion

Photon counting is that mode of operation where each detected photon results in a pulse at the anode of the photomultiplier. In this guide we have seen that certain high gain photomultipliers have the ability to detect single photons over a large photocathode area.

We have explained how the elements of a photon counting system are combined with the photomultiplier to produce an output count rate proportional to the intensity of light detected.

The relationship between the applied high voltage and that proportion of the output pulse height distribution actually counted leads to an understanding of the shape of the plateau characteristic.

The plateau characteristic curve is fundamental to optimising the system for photon counting and we have shown how this can be measured and how to choose the operating voltage.

In the last section we have looked at the options for realizing a photon counting system. The choice of discrete accessories or integrated modules. ET Enterprises is continually adding to the range of detector packages and we are always pleased to discuss your particular requirement with you. As a first step in choosing a light detector module please look at our web site: www.et-enterprises.com and select 'Photodetector Module' from the categories options in the search box on the home page.

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

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



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