Photomultiplier Tube Characteristics

PMT Specifications:

1) Overall Luminous Sensitivity (amperes/lumen [A/lm])- ratio of measured anode current at operating voltage to the luminous flux from a W light source of specified temperature incident on the photocathode.
2) Cathode Luminous Sensitivity (amperes/lumen [A/lm])- ratio of measured current of photoelectrons leaving the photocathode at operating voltage to the luminous flux from a W light source of specified temperature incident on the photocathode.
3) Overall Radiant Sensitivity (amperes/Watt [A/W])- ratio of anode current to radiant power at a given wavelength incident on the photocathode.
4) Cathode Radiant Sensitivity (amperes/Watt [A/W])- ratio of photocathode current to radiant power at a given wavelength incident on the photocathode.
5) Dark Current- anode current measured without illuminating the photocathode.
6) Anode pulse Rise Time- time taken for the output pulse to rise from 10% to 90% of the peak when the photocathode is illuminated by a flash of light of very short duration.
7) Anode Pulse Width- time width of the output pulse measured at half maximum amplitude for short duration illumination of the photocathode.

- Table 9.1 shows some properties of commercially available PMT's

Linearity:

- Nonlinearities for large pulses (where the size of the output pulse is no longer a measure of the number of the number of input photons) can arise from two main issues:
    1) Space charge effects from the last dynode to the anode where the number of electrons is the greatest.
    2) Deviation of the dynode voltages from their equilibrium value in the course of the pulse.
- Generally under normal circumstances and with an adequately designed tube base, the PMT response should be linear

Noise and spurious pulses:

- Stems from thermionic noise (dark current) or natural radioactivity (K-40 in the glass envelope) in the tube structure.
- Afterpulses- Satellite pulses that sometimes follow the true signal pulse after a short delay period, can be caused by:
    1) Emission of light from the latter states of the multiplier structure, which finds its way back to the photocathode.

2) Traces of residual gas in the tube, ionized by the passage of electrons through the multiplier structure. Positive ions formed will drift to the photocathode and release electrons from the photocathode.

Photocathode Non-Uniformities:

- The variable sensitivity found across the surface of large photocathodes, affecting the energy resolution of the system.
- Can be mitigated by using a light pipe between the scintillator and the end window of the PM tube.

Gain Variations with Counting Rate:

- If a divider string current is too low, it can lead to gain changes due to resulting changes in the dynode potentials.
- Another possible cause is from thermal and space charge effects created by the electron current passing through the multiplier structure.

Ancillary Equipment Required with Photomultiplier tubes

High Voltage Supply and Voltage Divider:

- Since electrons must be attached, the first dynode must be held at a voltage that is positive with respect to the photocathode, and each succeeding dynode must be held at a relative positive with respect to the preceding dynode.
- This can be done with individual cell sources, but is practically performed by a voltage divider circuit.
- Fig. 9.13 shows 2 common configurations for wiring the base of the PM tube. (a) Shows utilization of a positive high voltage and ground grounded cathode. (b) Uses a negative high voltage and insulates the photocathode from ground.
- Note that the equivalent load resistance R_L or R_L & R_L' is chosen so that the resulting anode circuit time constant is of proper magnitude.
- The capacitance C_A is not a physical capacitor, but the inherent stray capacitance in the anode structure and connecting cables.
- The current (direct) in the divider string is just the ratio of the voltage with the summed resistances along the string.
- For price keeping the current as small as possible is better, only when this current approaches the level of the internal current at the peak of the pulses, the dynode voltages begin to stray, so one wants a divider current large compared with the internal current.
- The problem is especially noticeable near the last dynode stages and stabilizing capacitors (C_s) are employed near the anode to hold these latter dynode voltages at a constant value through the pulse.
- In order to prevent a 1% change in the interdynode voltage, C_s*$V_{interdynode}$ or the charge Q on C_s must be 100 times greater than the charge emitted by that dynode during the pulse.

- The average current can be calculated by the product of the charge per electron ($1.6\text{x}10^{-19}$ C/electron), the number of electrons formed from a scintillation event, the gain of the PM tube, and the number of scintillation events per second, i.e.:

$$I_{avg}=1\text{x}10^{3}\text{ electrons/pulse}*1\text{x}10^{6}\text{ gain}*1.6\text{x}10^{-19}\text{ C/electron}$$
$$*10^{5}\text{ pulses/second}=0.016\text{ mA}$$

- The peak pulse is generally much higher and calculated by taking I_{avg} and dividing by the number of events times the pulse width: for an organic scintillator (extreme case) with a very fast decay time combined with the transit time produces a width of 5 ns.

$$I_{peak}=0.016\text{mA}/5\text{x}10^{-4}=32\text{ mA}$$

- Note that although the pulse polarity can be either negative (from the anode) or positive (from a later stage dynode which may be advantageous for some fast timing measurements), the resulting analysis is the same and the pulse polarity will be assumed to be negative.

Magnetic Shielding:

- The electron optics inside the PM are sensitive to stray magnetic fields (e.g. earth, MRI, etc.).
- Can be passively shielded using a mu-metal. Mu-metal is an alloy composition by weight: Fe: 18%; Ni: 75%; Cr: 2%; and Cu: 5%.

Photodiodes as Substitutes for PM Tubes

- Potential advantages: higher quantum efficiency (and better energy resolution), Lower power consumption, more compact size, improved ruggedness, and virtually insensitive to magnetic fields.

Conventional photodiodes:

- The basic configuration is shown in figure 19.14.
- The photodiode is a semiconductor where scintillation photons create electron-hole pairs in depleted regions. Note there is no multiplication of charges.

Avalanche Photodiodes:

- The electron-hole pairs formed in the interaction region are multiplied in the avalanche region by undergoing sufficient acceleration to form more electron-hole pairs.
- Fig. 9.17 shows the reach-through configuration of the avalanche photodiode. Note the larger voltage in the multiplying region.

Scintillation Pulse Shape Analysis

- We start with the simplified RC circuit of the PM tube (Fig. 9.18).

- If the spread of the transit time of the PM tube is small compared with the scintillation light decay time, the electron current arriving at the PM tube anode can be approximated by $i(t)=i_o e^{-\lambda t}$ where λ is the scintillation light decay constant.

- The total charge collected over the entire pulse is:

$$Q=\int_0^\infty i(t)dt = i_o\int_0^\infty e^{-\lambda t}dt = \frac{i_o}{\lambda};\ \ i_o=\lambda Q;\ \ i(t)=\lambda Q e^{-\lambda t}$$

Current flowing into the parallel RC circuit is: $i(t)=i_C+i_R$

$$i(t)=C\frac{dV(t)}{dt}+\frac{V(t)}{R}$$

Substitute in i(t) to get the in-homogeneous differential equation:

$$\left(\frac{\lambda Q}{C}\right)e^{-\lambda t}=\frac{dV(t)}{dt}+\left(\frac{1}{RC}\right)V(t)$$

Solving the homogeneous solution (set = 0)

$$\frac{dV^H}{dt}+\left(\frac{1}{RC}\right)V^H=0$$

$$let\ \ \theta=\frac{1}{RC}\Rightarrow V^H(t)=Ae^{-\theta t}$$

For the particular solution let $V^P(t)=Be^{-\lambda t}$, then substitute into the inhomogeneous equation:

$$\frac{dV^P(t)}{dt}+\frac{1}{RC}V^P(t)=\frac{\lambda Q}{C}e^{-\lambda t};\ \ where\ \ B=\frac{\lambda Q}{(\theta-\lambda)C}$$

Overall the solution is given by $V(t)=V^H(t)+V^P(t)$ and for initial conditions of $V(0)=0$ we can get A:

$$A=-\frac{\lambda Q}{(\theta-\lambda)C}$$

- The overall solution is then:

$$V(t)=\frac{1}{\lambda-\theta}\cdot\frac{\lambda Q}{C}\left(e^{-\theta t}-e^{-\lambda t}\right);\ \ \theta=\frac{1}{RC}$$

- For a large time constant ($\theta<<\lambda$) compared to scintillator decay time:

$$V(t)\approx\frac{Q}{C}\left(e^{-\theta t}-e^{-\lambda t}\right)$$

But θ decays slowly with respect to λ so for short times ($t<<1/\theta$), the second exponential dominates and $V(t)\approx\frac{Q}{C}\left(1-e^{-\lambda t}\right)$,

After a sufficiently long time ($t>>1/\lambda$) the second exponential decays to 0 and the first exponential dominates and $V(t)\backslash\approx\frac{Q}{C}e^{-\theta t}$ so:

1) Leading edge of the pulse behaves as $1-e^{-\lambda t}$, determined by scintillation time.
2) Trailing edge of the pulse $\sim e^{-\theta t}$, determined by time constant $RC\equiv 1/\theta$.
3) Amplitude of the pulse is Q/C, but is only reached if $\theta<<\lambda$ or the anode circuit time constant must be large compared with the scintillator decay time.

- For small time constant ($\theta >> \lambda$):

$$V(t) = \frac{\lambda}{\theta} \cdot \frac{Q}{C}\left(e^{-\lambda t} - e^{-\theta t}\right)$$

for small t ($t << 1/\lambda$): $V(t) = \frac{\lambda}{\theta} \cdot \frac{Q}{C}\left(1 - e^{-\theta t}\right)$

for large t ($t >> 1/\theta$): $V(t) = \frac{\lambda}{\theta} \cdot \frac{Q}{C} e^{-\lambda t}$

1) Leading edge determined by $1-e^{-\theta t}$.
2) Trailing edge determined by $e^{-\lambda t}$.
3) Maximum amplitude is now $\lambda Q/\theta C$, much smaller than before since by definition $\theta >> \lambda$.

- Figure 9.19 shows the plot of the two extremes for the time constant, where for case 2 the pulse is much shorter, but amplitude is also much smaller.

<u>Hybrid PM Tubes (HPMT)</u>

- Fig. 9.21 shows the elements of a HPMT with the photocathodes focus onto a silicon detector.
- Basically, the photoelectrons released from the photocathode are accelerated and interact with the semiconductor detector.

<u>Position Sensing PMT's</u>

- Figs. 9.23 and 9.24 show two examples of arrays of multiplying structures within the PMT.
- These different arrays of dynodes correspond to different regions of the photocathode and retain positional information.