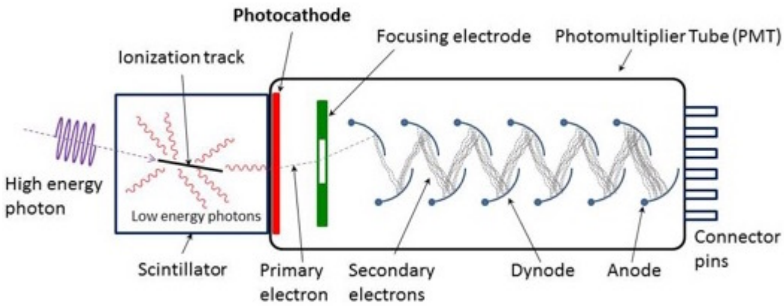
Radiation Detector 2018/19 (SPA6309)

Photo-multiplier tubes (PMT)

Basic concept of PMT (Leo, 8.1)

Photo-multiplier tubes (PMTs) is a photon detector often combined with scintillators. Incident photons are absorbed by the **photo-cathode**, and photo-electric effect produce **photo-electrons.** Then, electric field focuses electrons on the **dynode**, collision of electrons on dynode produce more electrons, which is now focused to the second dynode to produce more electrons etc..., and finally, a cascade of electrons is obtained as a large electric pulse. The multiplication coefficient is called **gain**, and a typical gain is $\sim 10^7$, so one photon becomes roughly 10 million electrons.



An important parameter is the efficiency of photo-electron emission per incident photons, called **quantum efficiency** (definition of quantum efficiency is inconsistent between literature, we stick to this simple definition).

$$QE = \frac{photo\ electrons}{incident\ photons}$$

Typical QE has a peak around 400nm (blue light). If the incident photon wavelength is too short (=UV), photons are absorbed by the glass window and QE is low. If the incident photon wavelength is too long (=infrared), the energy of the photon is low and photo-electron is not emitted. Not surprisingly, many scintillators are "tuned" to emit scintillation light around 400-450nm so that it's easy to detect by PMTs. For example, for the application of liquid argon scintillation detection, TPB (WLS) emission peak is ~400-450nm.

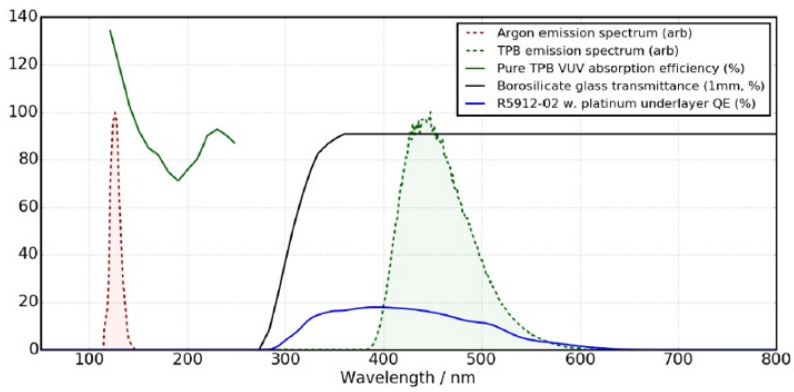
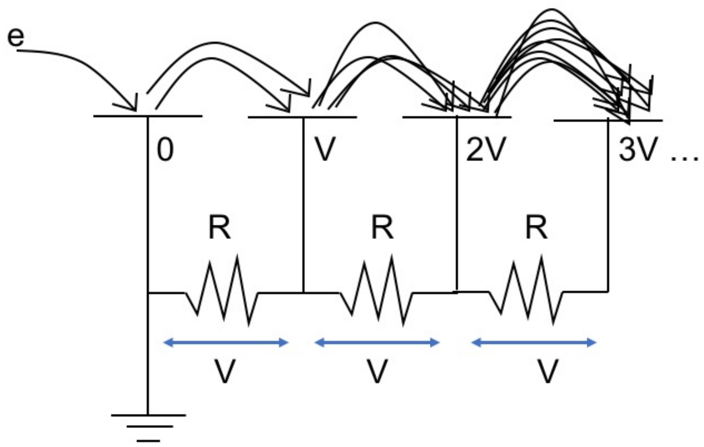


Photo-cathode is made by metals such as Sb, Rb, K, Cs (all toxic). Since PMTs have a vacuum, handling of PMTs, in general, need care because their "implosion" (not "ex"plosion) are considered to be dangerous.

Electron multiplication (Leo, 8.4)



At each stage, different voltages are applied. The best way is to apply **high voltage (HV)**, and split it by resistors. This is an example of the circuit called **voltage divider.**

Each stage, electron number increase $\delta \sim KV$, so the total gain G for n-stage PMT is $G = \delta^n = (KV)^n$. To achieve certain gain G, what is minimum supply voltage V_b?

$$V_b = nV = n\frac{G^{1/n}}{K}$$

$$\frac{dV_b}{dn} = \frac{1}{K}G^{1/n} - \frac{n}{K}\frac{G^{1/n-1}}{n}\frac{dG}{dn} = 0, \frac{1}{G}\frac{dG}{dn} = 1 = \frac{d}{dn}(lnG)$$

Thus, $n = lnG$. To achieve 10^7 gain, we need n~16, or 16 stages. If each stage has 100 V difference, we need a necessary minimum supply voltage $V_b \sim 1600V$. A typical HV for PMT operation is around 1kV-2kV. Typical resistor values are ordered 100kΩ, and the total resistance of the voltage divider is around 1MΩ. This means there are only 1.6μA current flowing to the voltage divider (I=V/R). So the PMT operation needs HV, but the required current is very low.

Now, what is the fluctuation of the gain?

$$\frac{dG}{G} = \frac{ndV}{V} = \frac{ndV_b}{V_b}$$

For example, for the 10-stage PMT, 1% fluctuation of V_b will make 10% gain fluctuation. Therefore, for a stable operation of PMT, stable HV power supply is essential.

The typical voltage dividers have following structure. It is common to use slightly larger resistors at the beginning and the end. There are 2 types of operation. **Positive HV** operation means the photo-cathode to be ground, and the last stage to be high voltage. On the other hand, **negative HV** operation apply negative HV to the photo-cathode, and the last stage to be ground. This operation has an advantage for safety (output is small voltage), but the HV at the photo-cathode which in general makes larger noise.

Noise (Leo, 8.7)

PMTs count photons and they are very sensitive devices. There is a variety of noise, but the most common one is the **thermionic emission** (spontaneous emission) of photo-electrons from the photo-cathode and makes a signal, even though no photons hit the photo-cathode.

Application

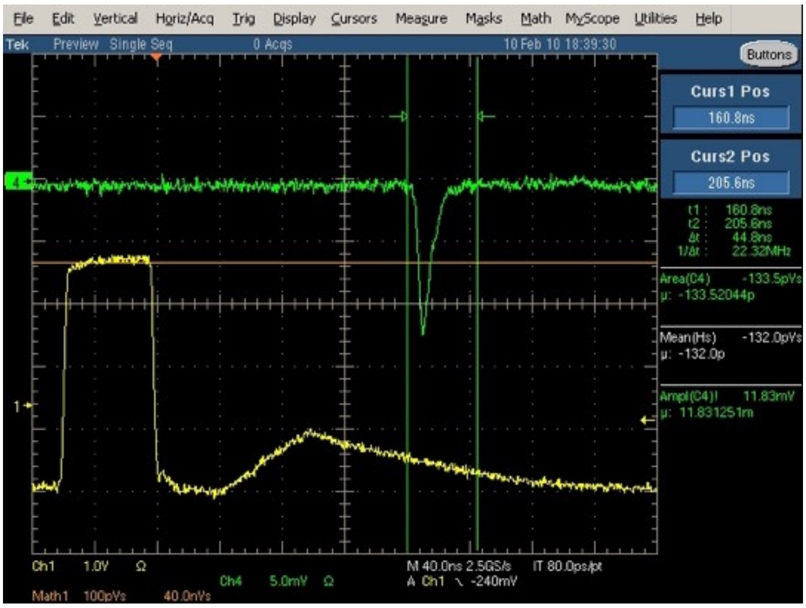
Here, we tested PMTs in a tank (these are special cryogenic PMTs tested in liquid nitrogen), https://arxiv.org/abs/1304.0821 (https://arxiv.org/abs/1304.0821) (JINST8(2013)T07005). Tested PMTs are successfully installed in the MicroBooNE detector (https://arxiv.org/abs/1612.05824 (https://arxiv.org/abs/1612.05824))

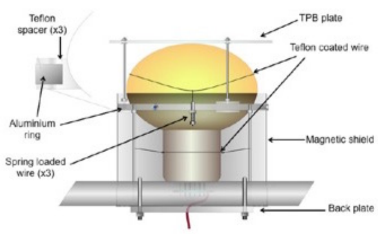
The green curve shows a typical PMT pulse from photons. Let's estimate how many photo-electrons are initially produced for this pulse. First, the size of the pulse is roughly 13mV, and the duration is 20ns. By approximating this is a triangle, then the area is $1.3 \times 10^{-10} V \cdot s$.

$V = I \cdot R \rightarrow V \cdot s = Q \cdot R$, here $R = 50\Omega$ because oscilloscope can be adjusted to 50Ω so that the signal from 50Ω impedance cable is not reflected. The charge Q is number of photo-electrons × gain × Coulomb (=1.6×10^{-19})

$$1.3 \times 10^{-10} = PE \cdot 10^{7} \cdot 1.6 \times 10^{-19} \cdot 50$$

$PE = 1.6$, so roughly 1.6 photo-electrons are produced by incident photons. Of course, numbers of both incident photons and photo-electrons are an integer at each event but estimated PE can be a fractional number.





Pedestal

Data can be the integral of the pulse (pulse area). However, every pulse is on top of electric noise, and even there is no signal pulse, integral is nonzero. This is called **pedestal**, and the histogram of data often makes a huge peak at the first bin. We re-define this is zero of the measurement. For example, here the peak is at ~77, but this peak is made by 1 photo-electron detection + noise. Since pedestal is ~40, an actual charge corresponding to 1 photo-electron detection is channel 37. As we see before, zero observation has lots of application due to Poisson statistics.