Quantum Efficiency, Gain, and Nonlinearity Measurements of Photomultiplier Tubes

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Abstract

We present the results of a project aimed at the quantitative characterization of the electrical and optical properties of photomultiplier tubes (PMTs). The PMTs used for testing were manufactured by ET Enterprises, and they include standard as well as extended linear range designs intended for use under high light levels. We have developed two different experimental setups to characterize PMTs. The first setup performs an absolute measurement of quantum efficiency (QE) and gain over the 200-900 nm wavelength range by using illumination with a tunable light source (TLS) in combination with an integrating sphere. Gain curves are measured at several high voltages chosen specifically for each PMT. The second setup measures the linearity in the PMT response using illumination with two double-pulsed 401 nm lasers. We explain the setups and measurements in detail.

Introduction

Our Goal

We want to create a characterization procedure that will measure the QE, Gain, and Nonlinearity of photomultiplier tubes. The obtained results will feed into a Monte Carlo simulation which will be used to simulate detection of Cherenkov radiation.

What are Photomultiplier tubes (PMTs)?

- PMTs are highly sensitive light detectors capable of single photon detection.
- They work by converting light signals into readable electrical current.
- They can detect a wide range of wavelengths from the near-infrared to the ultraviolet.
- They are widely used in areas such as astronomy, astroparticle, low/high energy, nuclear, biological, and medical applications.

QE

A light sensitive material called the photocathode converts incoming photons into photoelectrons through the photoelectric effect. The efficiency of the photocathode is known as the Quantum Efficiency (QE). QE is defined as:

$$QE = \frac{Number\ of\ photoelectrons}{Number\ of\ incident\ photons}$$

Gain

The created photoelectrons are then focused and accelerated towards the first dynode using electron optics. The dynodes are used to cause an electron multiplication chain via secondary electron emission. How much the current increases is known as the Gain of the tube.

Nonlinearity

Using a three pulse configuration (Figure 1), We will define nonlinearity as:

$$Nonlinearity = 100 \cdot \left(\frac{Pulse\ 3}{(Pulse\ 1 + Pulse\ 2)} - 1\right)$$

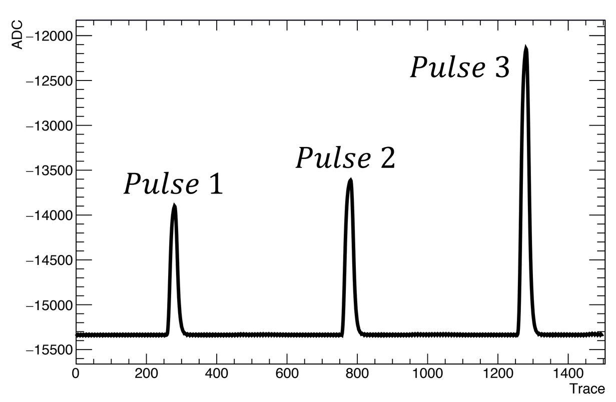
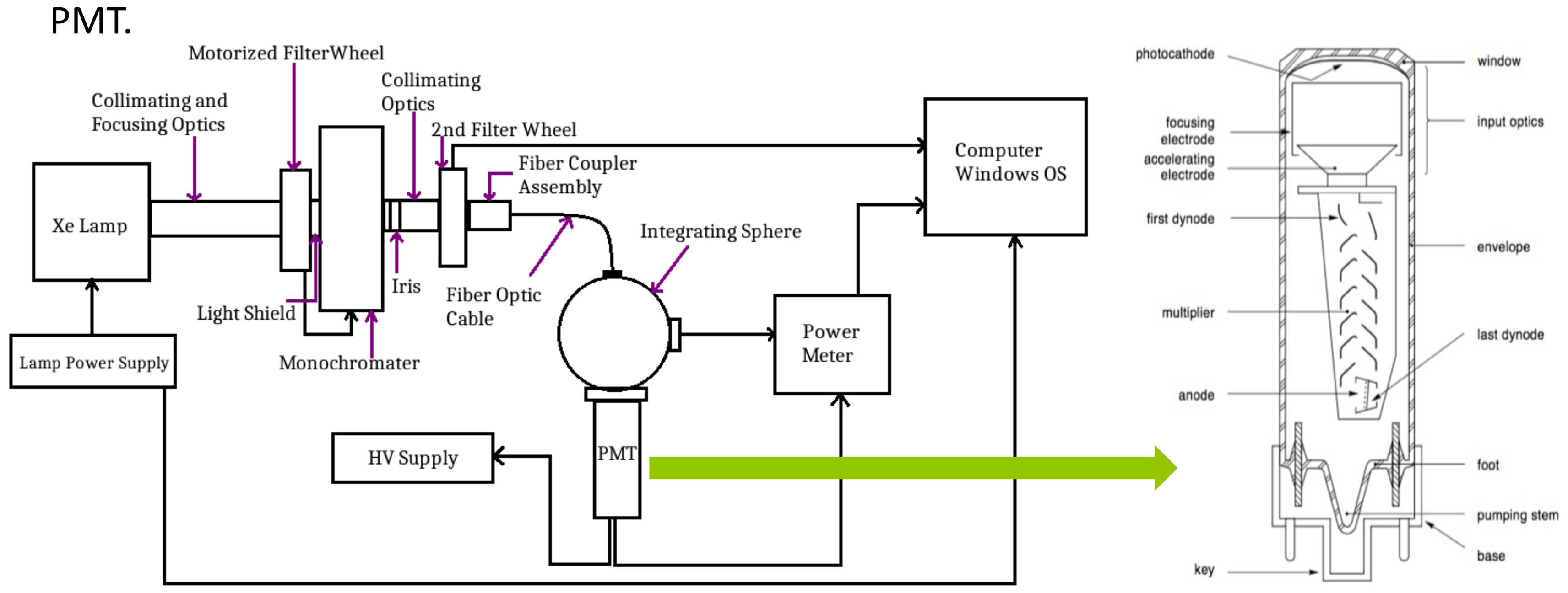


Figure 1. Using two lasers and a function generator we can create three pulses. Three pulses are needed to cancel possible laser light fluctuations. The third pulse is the sum of the first two in the linear regime.

Quantum Efficiency and Gain

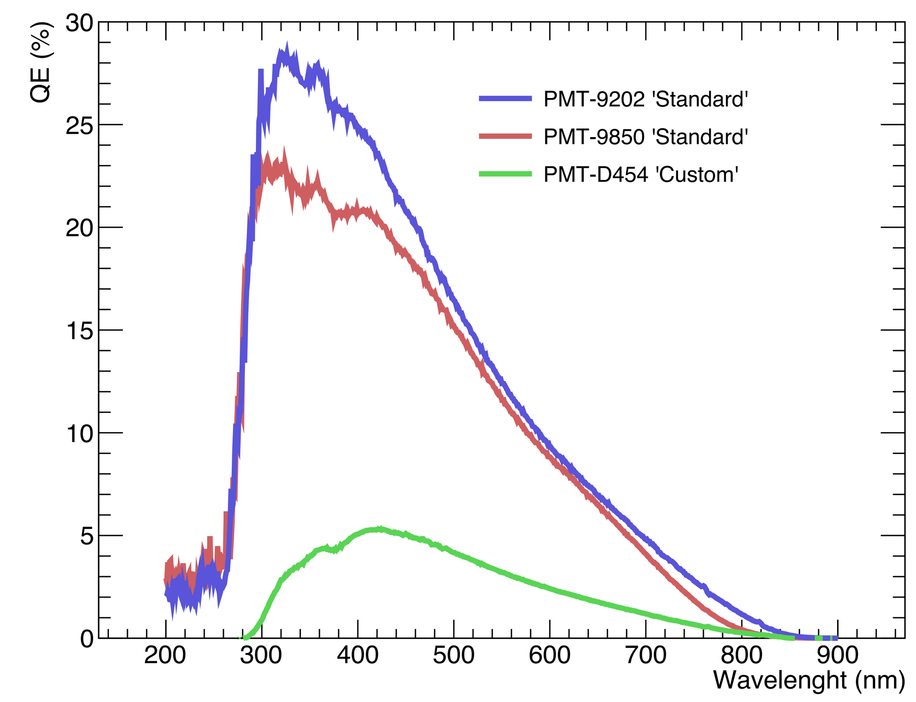
Setup

- We use a tunable light source which can output wavelengths between 250 - 1100 nm. The light is then collimated into an light guide ending at an integrating sphere. A NIST calibrated photodiode is used the measure the number of incident photons onto the PMT.



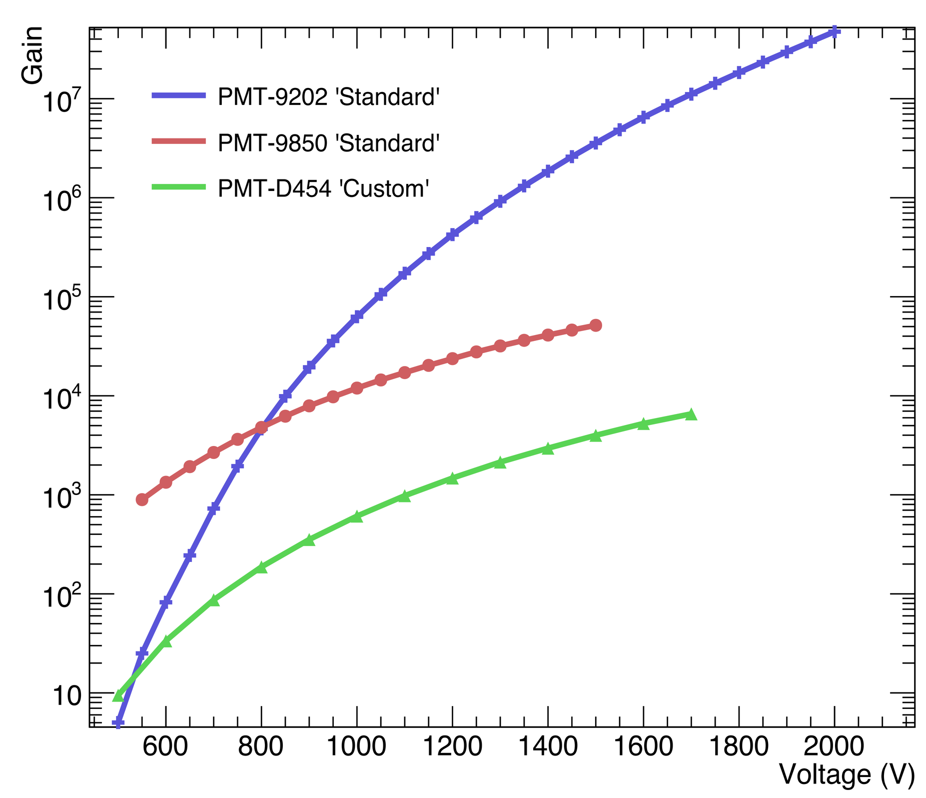
Results

- QE



- The standard PMTs have a Quartz window which transmits down to 200 nm. The custom tube has a borosilicate window that only transmits down to 300 nm.
- The custom tube has an added platinum layer at the photocathode which increases the linear range but decreases its QE.
- The 9202 shows a maximum QE of 28.4% ± 2.5% at 322 nm. The 9850 has a max QE of 23% ± 2.5% at 320 nm. The D454 has a max QE of 5.3 ± 2.5% at 421 nm.

- Gain

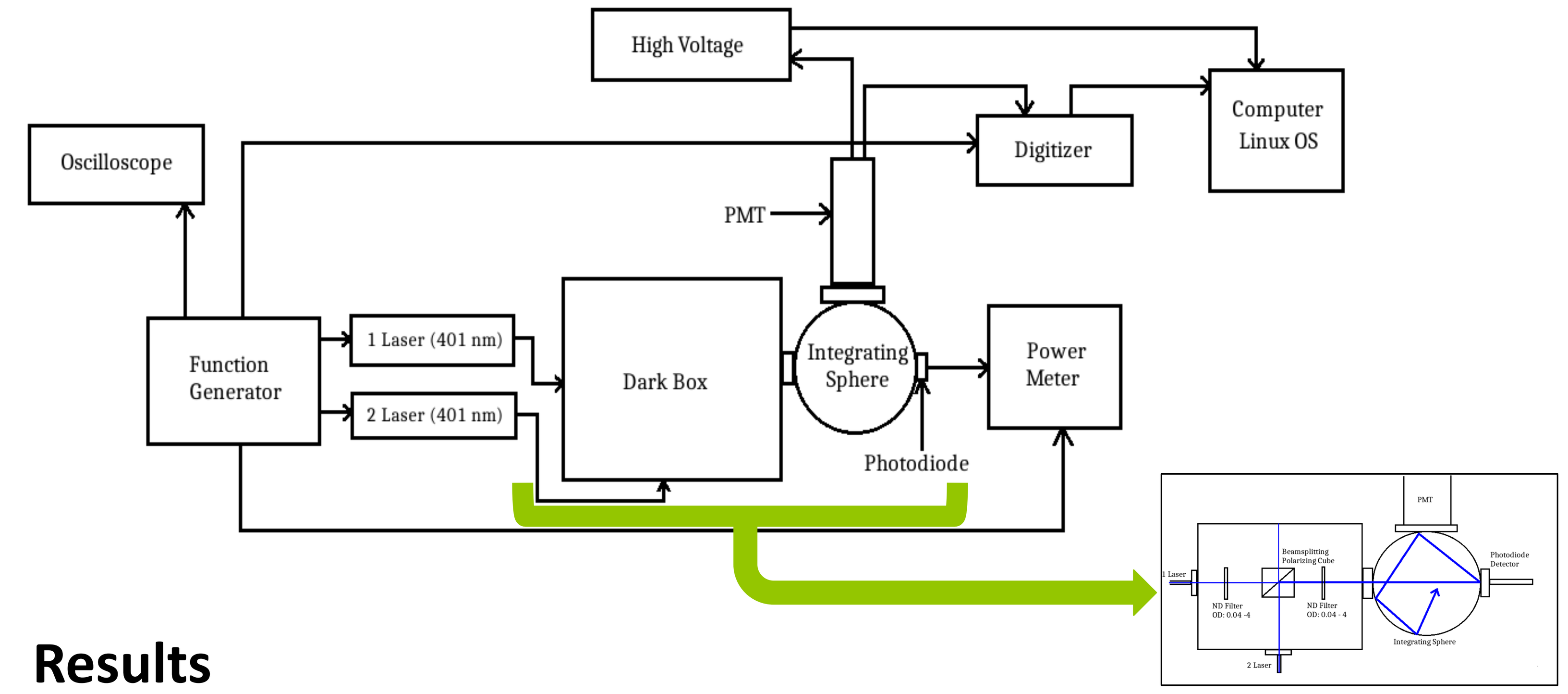


- Increasing the high voltage increases the current. This allows us to have control over how much amplification we desire depending on our application.
- The 9202 tube has 12 dynode stages and high gain. The 9850 and D454 tubes have only six dynodes and correspondingly lower gain.
- The difference in gain between the D454 and the 9850 is due to a different base (resistor network) configuration.

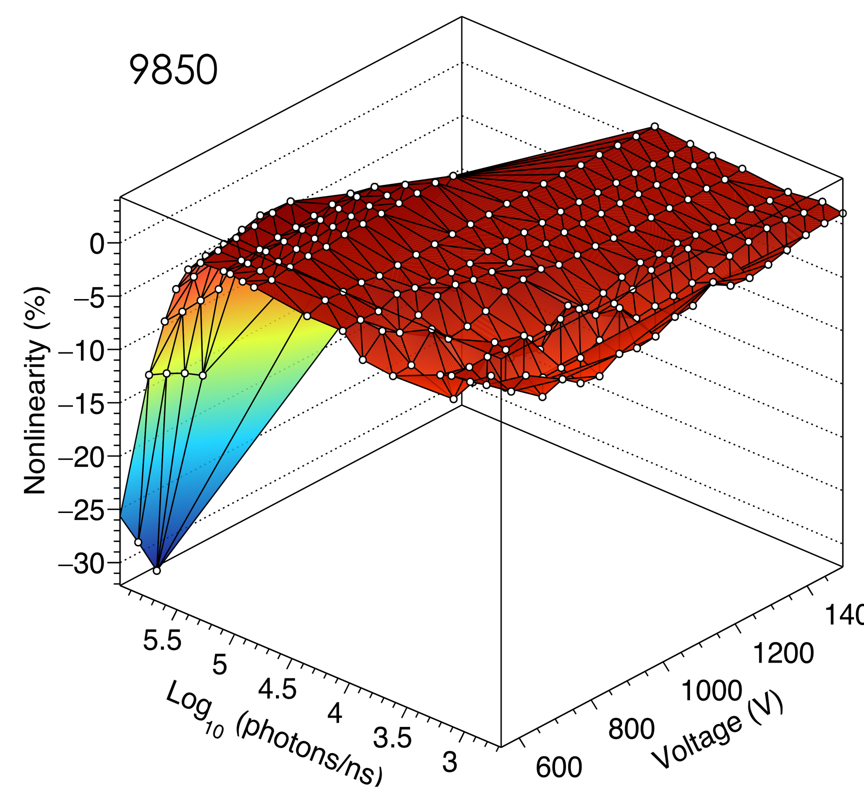
Nonlinearity

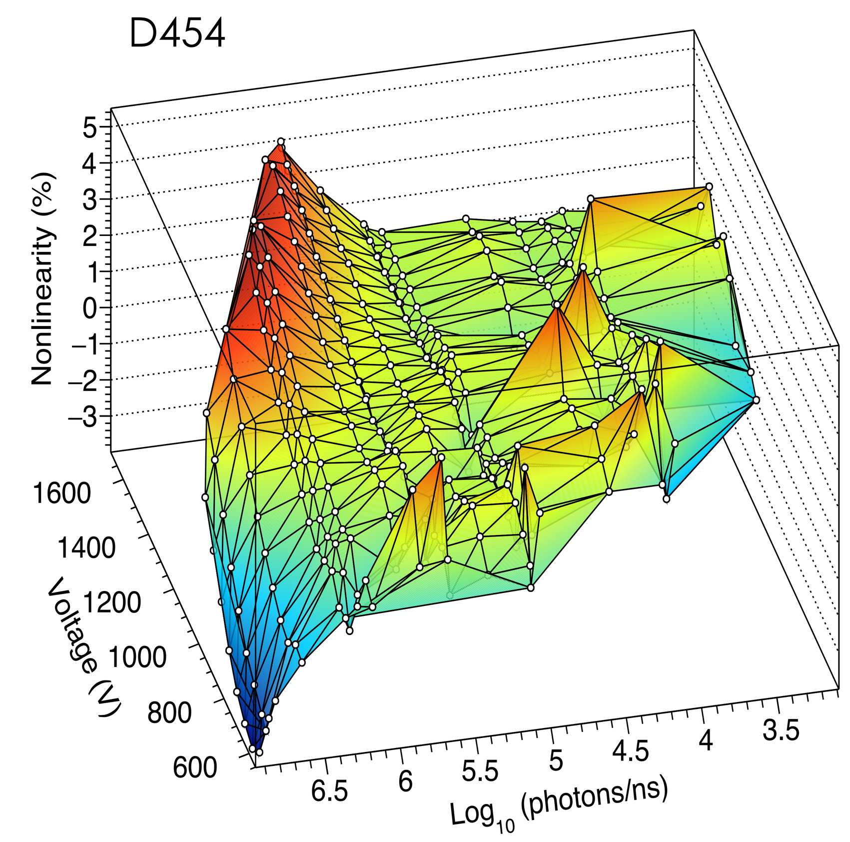
Setup

- Two 401 nm lasers are set up to give us a three pulse configuration (see Figure 1). They are combined and attenuated inside a dark box and injected into an integrating sphere.



Results





- The nonlinearity was measured at multiple voltages and light intensities.
- The photocathode of the 9850 tube enters the nonlinear regime above $10^{5.5}$ photons/ns and 600 V. From this point on there is no charge left in the photocathode to create photoelectrons and therefore we observe a nonlinear behavior that increases rapidly.
- The D454 is a custom tube that shows better linearity at higher light levels.
- The D454 also shows nonlinearity at the backend (last few dynodes plus anode) of the tube. This is caused by high voltage and high light intensities.
- Each Model of PMT has a specific voltage range within which it can be operated.
- The ideal tube exhibits linear behavior over a wide range of light intensities.

Discussion

The D454 is a modified tube that contains a thin platinum layer at the photocathode with the goal of increasing its linearity at high light levels. We can observe that this is consistent with our results as the tube shows linear behavior up to 10^6 photons/ns. In contrast, the standard low-gain, high linearity 9850 tube stays linear up to just $10^{5.5}$ photons/ns. However, obtaining high linearity comes at a cost since the amount of gain that can be achieved is much lower. In addition, the D454 also shows lower QE. This is also caused by the platinum layer which affects the photon/electron interactions at the photocathode.

Conclusion

Both our QE/Gain and Linearity measurements are consistent with our expectations. The standard tubes (9202 and 9850) show QEs that extend deep into the ultraviolet region; this is caused by the Quartz window which transmits wavelengths down to 200 nm. On the other hand, the D454 contains a borosilicate window that can only transmit down to ~300 nm. Furthermore, the high-gain 9202 tube shows much higher gain than the lower gain tubes (9850/D454) as expected from the different dynode architecture. Also, the D454 stays linear at higher light levels than the 9850; however, the added modifications cause it to have a much lower QE.

References

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3. G. F. Knoll, *Radiation Detection and Measurement*, (John Wiley & Sons, Inc, 2000), Chap. 9.

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