Dark Matter Detection and PMT Base Optimization

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Abstract

The purpose of the research presented in this paper is to help characterize and improve the photomultiplier tubes which go inside the Xenon dark matter detector. This paper discusses Dark Matter, the Xenon experiment, and the main project. The main project presented in this paper is the optimization of a parameter of photomultiplier tubes called linearity. Linearity means that the input and output signals of the PMT should form a linear relationship. Five different parameters were scanned in this experiment to determine their effect on the linearity of the PMT.

1 Introduction to Dark Matter

1.1 Evidence for Dark Matter

Dark Matter makes up nearly 25% of all matter in the universe, yet very little is known about it. Dark matter is hypothesized to exist because certain cosmological phenomenon cannot be explained without it. For example, based on Newton's law of gravitation, it is expected that as the distance from a galaxy's center increases, the rotation velocity of an object decreases. However, it is observed that this velocity actually increases. This can be explained with a spherical halo of dark matter surrounding these galaxies (Bertone et al. 2008). This is just one of many examples of evidence for dark matter. Other evidence includes many different types of galactic formations as well as the cosmic microwave background. Furthermore, dark matter is a necessary catalyst for structure formation in the universe. Without non-relativistic massive particles to slow down the hot soup of relativistic particles present in the early universe, these particles would have too high an energy to come together to form stars and galaxies. Because of all of this, understanding more about dark matter is very important from a cosmological and astrophysical point of view. Understanding the precise nature of dark matter particles would give astronomers another lens through which to view the universe, its structure, and its formation.

1.2 Dark Matter Candidates and the WIMP

Because so little is known about dark matter, physicists are now developing methods of detecting these particles. The first question to ask is, "What are we looking for?" Different detection techniques are used to detect different types of particles, and for this reason, physicists must have a particle in mind when attempting detection. A dark matter candidate must meet certain requirements. Most importantly, it must be a massive particle which does not emit or absorb electromagnetic radiation. It must be massive because it interacts gravitationally and it must not emit or absorb electromagnetic radiation because it is "invisible". Aside from these main requirements, it is predicted to be non-relativistic, non-baryonic, and abundant enough to comprise 25% of the matter in the universe (Bertone et al. 2008). No particle which meets all the requirements of a dark matter candidate appears in the standard model of particle physics. For this reason, understanding more about dark matter is also of particular interest to particle physicists. Finding a dark matter candidate means looking outside the standard model to new realms of physics. The focus of this paper and the Xenon experiment is the WIMP (weakly interacting massive particle). The WIMP is an umbrella term for several theorized particles with similar masses and interaction cross-sections. The interaction cross-section of the WIMP is on the order of a weak interaction, thus the name "weakly interacting". The most promising constituent of the WIMP umbrella is the neutralino. This refers to any neutral supersymmetric particle (Jungman et al. 1996). This includes the Wino, Zino, and Higgsino, the supersymmetric pairs of the W boson, the Z boson, and the Higgs Boson.

2 The Xenon Experiment

The Xenon experiment uses a dual-phase detection method to detect WIMP-like particles. Recently, in July 2012, the Xenon 100kg detector set the world's leading limit in the WIMP search. Xenon is used for several reasons. First, noble gases are commonly used in detectors of this type because they are generally non-reactive. Furthermore, Xenon is specifically useful because it does not have any common radioactive isotopes which can cause unwanted background signals. This is especially relevant when comparing Xenon detectors to Argon detectors because Argon occurs in nature mostly as a radioactive isotope. Lastly, the interaction cross-section for a WIMP particle and a Xenon nucleus is ideal (Arpile et al. 2012).

2.1 The Detector

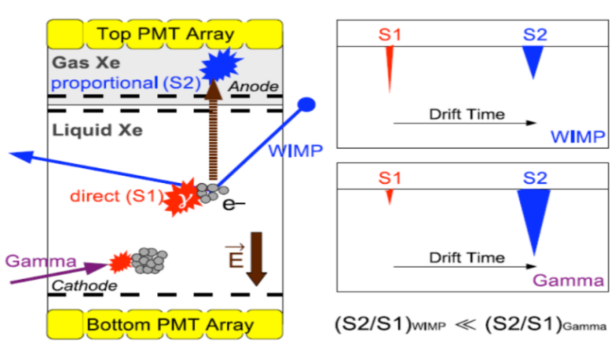


Figure 1: Xenon Detector Diagram

The detector is a large tank filled with liquid Xenon with a small top layer of gas Xenon. The bottom and top of the detector is lined with photomultiplier tubes. A WIMP particle will enter the detector and hit a Xenon nucleus. This causes the electrons to be released from the atom and then recombine on the nucleus. This produces a light signal on the order of a single photon which is called "S1". This signal is detected in the bottom array of PMTs. In the detector, there is an electric field pointing downward. This field causes some of the electrons released from the Xenon nucleus to drift upwards through the gas xenon. This causes a second signal on the order of 10^6photons to be detected by the top array of PMTs. This is called the "S2" signal. Having the two signals helps in a few ways. First, comparing the ratio of these two signals can help to differentiate between WIMP signals and background radiation such as gamma. Secondly, the S2 signal helps with the position reconstruction of events (Arpile et al. 2012).

2.2 Photomultiplier Tubes

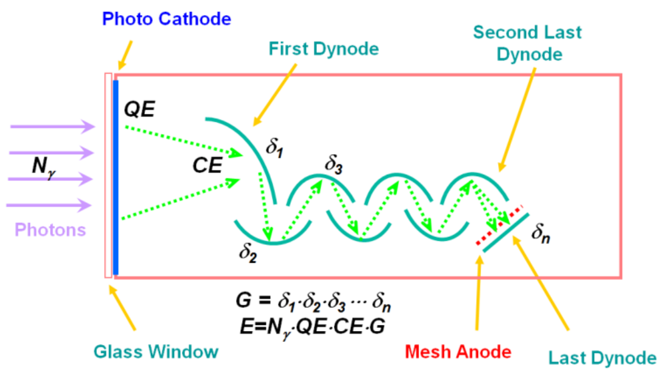


Figure 2: PMT Diagram

A PMT is a very sensitive instrument which converts a light signal to an electrical signal by use of the photoelectric effect. There is a photocathode and an anode at opposite ends of the PMT. In between, there is a series of dynodes designed to multiply the number of electrons. A photon enters the photocathode which releases a photoelectron. This photoelectron hits the dynodes, each one multiplying the number of electrons until they reach the anode. In the PMTs used for this experiment, for each photoelectron released at the photocathode, there will be around $5 * 10^6$ electro ns at the anode. This is called the gain of the PMT (Lung et al. 2012).

2.3 Linearity and Saturation in Xenon100

In the Xenon100 experiment, there was a problem with the top array of PMTs. PMTs have a property called linearity. What this means is that the input signal should form a linear relationship with the output signal. However, at a certain point, the PMTs become saturated and this relationship is no longer linear. When a PMT becomes saturated, the electrons between the last few dynodes begin to repel each other off course. As discussed previously, the S1 signal is on the order of a single electron while the S2 signal is on the order of 10^6 photons. This means the PMTs need a very large range so they do not become saturated. In Xenon100, the top array of PMTs was experiencing this saturation. This hurts both the energy threshold and the position reconstruction capabilities of the detector (Arpile et al. 2011).

2.4 The Upgrade to Xenon1T

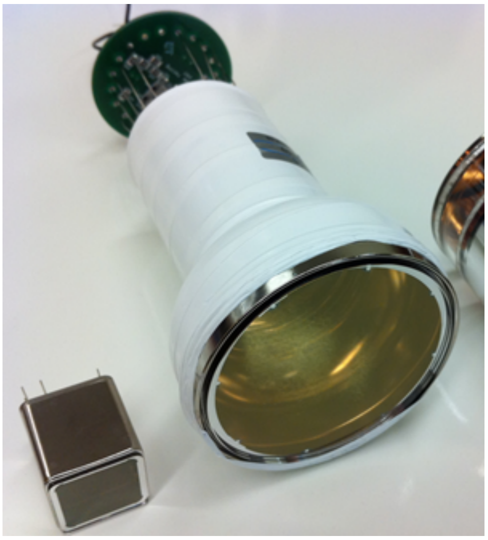


Figure 3: Left- One inch PMT from Xenon100. Right- Three inch PMT for Xenon1T (R11410).

Currently, the Xenon collaboration is in the process of upgrading from a 100kg detector to a one tonne detector. This upgrade includes upgrading the PMTs from one inch to three inches. To do this, the new PMTs must be characterized and tested. One task in all of this is to optimize the linearity of these PMTs to ensure that the Xenon1T experiment does not experience the same problem as the Xenon100 experiment. In doing the following calculation, we can determine the current the PMTs need to be linear up to. For each keV of energy of the incoming particle, it is expected that 350 photoelectrons will be released in the top array of PMTs.

$$\text{Assuming } \frac{350pe}{keV}$$

The largest expected signal is 3000keV, so the number of photoelectrons released will be:

$$\frac{350pe}{keV} * 3000keV = 1.05 * 10^6 pe$$

Multiplying this by the gain of the PMTs, the number of electrons at the anode is calculated:

$$e\ at\ Anode = 1.05 * 10^6 pe * 5 * 10^6 = 5.25 * 10^{12} e$$

Using the pulse width of 1μs, this is converted to current:

$$Q = 5.25 * 10^{12} e * 1.602 * \frac{10^{-19} C}{e} = 8.4105 * 10^{-7} C$$

$$I = \frac{8.4105 * 10^{-7} C}{1 * 10^{-6} s} = .84105\ A$$

Assuming a maximum of 15% of photons will hit any single PMT, the max current a PMT will need to handle is:

$$I_{center} = .15 * .84105\ A = .126158\ A = 126.2\ mA$$

3 Linearity and Base Optimization

To optimize and explore the linearity of these PMTs, different components were changed on the base. The base of the PMT is a series of resistors and capacitors which connect each dynode. Essentially, the resistance in between each dynode controls the strength of the electric field in between these dynodes. By exploring different combinations of resistances and capacitances, linearity can be optimized. Over the summer, five different parameters were explored:

Resistor Ratio: This is the ratio of resistances of the last three resistors. The electron cloud inside the PMT is only dense enough to cause saturation between the last three dynodes. Changing the ratio of the resistors in this area can help to minimize this saturation.

Resistance: Changing the overall magnitude of the resistors in the chain affects the linearity of these PMTs greatly.

Capacitance: Because capacitors are sources of radioactivity, a smaller capacitance is preferred. It is important to know what is sacrificed in terms of linearity when smaller capacitors are used.

Number of Capacitors: It is standard to have four capacitors in these PMTs, one between each of the last four dynodes. This measurement explores how linearity is affected when this number is reduced.

Trigger Frequency: This explores how the rate at which the PMT receives signals effects its linearity.

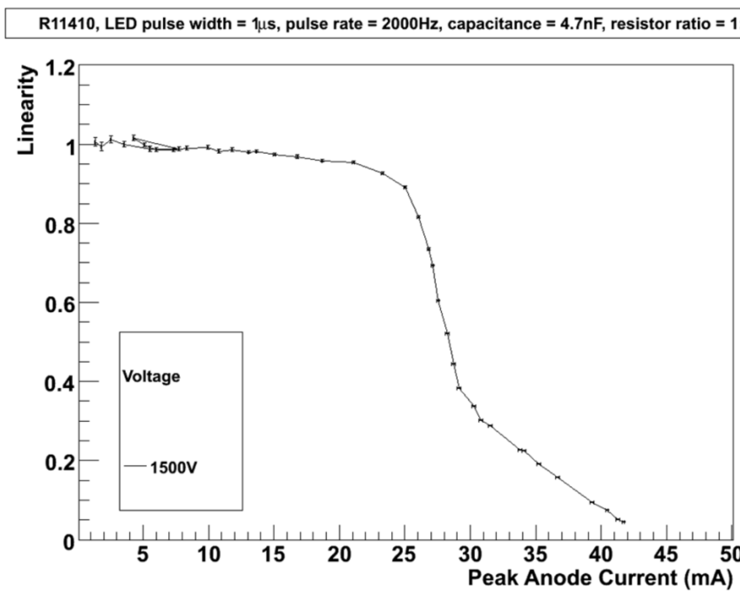
3.1 The System

To test the linearity of a PMT, an LED pulses at a 3:1 ratio of intensities. This light is passed through two rotatable filters, a discrete filter and a continuous filter. These filters change the amount of light which reaches the PMT. If the input signal pulses at a 3:1 ratio, it is expected that the output signal also pulses at a 3:1 ratio. However, by increasing the light intensity using the filters, one can observe the point at which the ratio of output signals degrades from 3:1. This is the point at which the PMT has become nonlinear. This point is defined as the point at which linearity deviates by 5%. Using this method, the aforementioned parameters were scanned.

4 Results

4.1 Resistor Ratio

Here, the ratio of the resistors between the last three dynodes was changed. In doing this, the hope was to optimize the ratio of the electric fields to conserve as much charge as possible. Three different resistor ratios were scanned. The standard ratio was 1:2:1. This was compared to a ratio of 1:1.5:1.5 and 1:2:3.



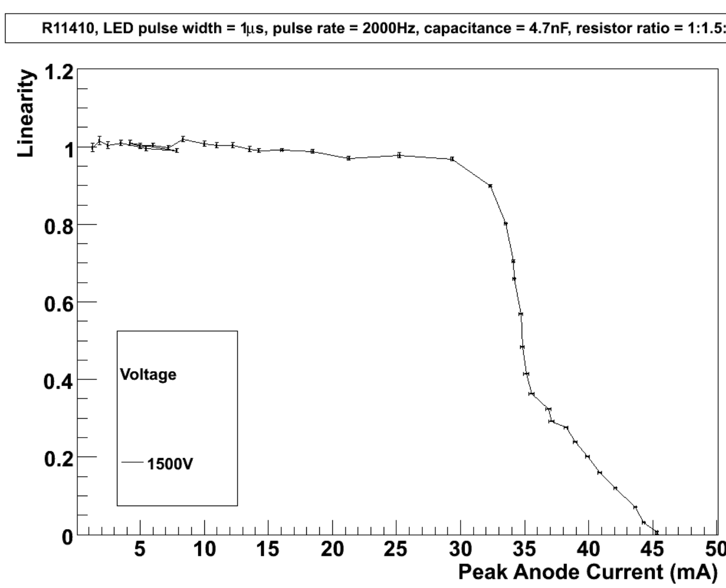


Figure 4: Top- Linearity graph for a resistor ratio of 1:2:1. Bottom: Linearity graph for a resistor ratio of 1:1.5:1.5

As seen in Figure 4, the deviation from linearity for a resistor ratio of 1:2:1 occurs around 25mA. However, when the ratio is changed to 1:1.5:1.5, the deviation occurs at around 33mA. The ratio of 1:2:3 caused erratic results. So, by changing the ratio of the resistors to 1:1.5:1.5, the linearity of the PMTs was increased without any negative side effects and this ratio was adopted as the new standard.

4.2 Resistance

In this measurement, the magnitude of the resistors was changed. Originally, the standard was to use R=1MΩ resistors. All other measurements were taken with this standard. However, this resistance is too low to use in the actual detector. In the actual detector, power consumption is a real concern. Power costs money and there is a limit to how much can be spent on it. For this reason, it would be ideal to use larger resistors in order to reduce the power consumed by the detector. To test the linearity of larger resistors, the resistance was changed to R=10MΩ.

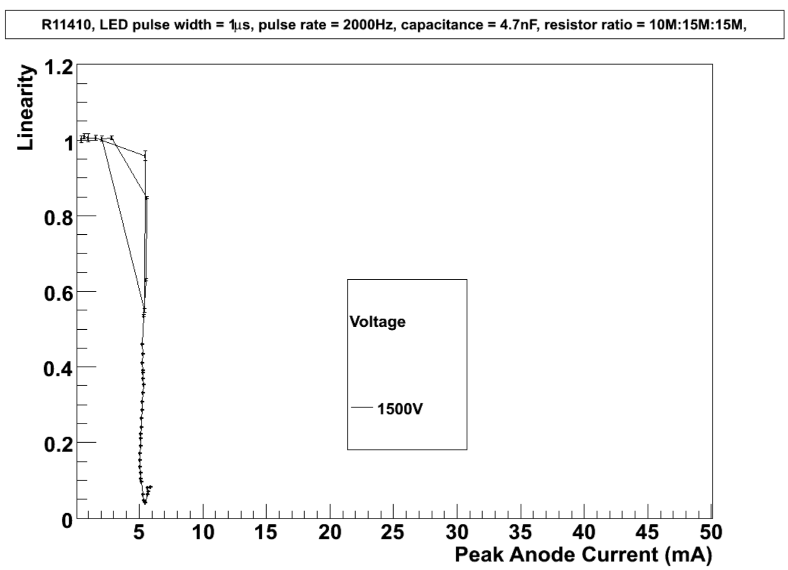


Figure 5: Linearity graph for R=10MΩ.

As seen in Figure 5, increasing the resistance greatly reduced the point at which linearity deviates. Using 10MΩ resistors caused the PMT to deviate from linearity at around 4mA. Considering that in the actual Xenon1T detector, larger resistors will be used, this is an important measurement. Now that it is known how greatly the larger resistors effect linearity, additional measures must be taken to account for this. For instance, by reducing the voltage at which the PMTs operate and adding an amplifier to the output signal, linearity can be restored. Solutions like this one must be implemented to account for the lost linearity.

4.3 Capacitance

Ceramic capacitors are sources of radioactivity. For this reason, having smaller capacitors is advantageous in the actual detector. There are four capacitors; one between each of the last four dynodes. The capacitors help linearity because they help to re-supply the charge lost due to saturation. Three different sizes of capacitors were scanned. The standard, 4.7nF was compared to 100nF and 1nF.

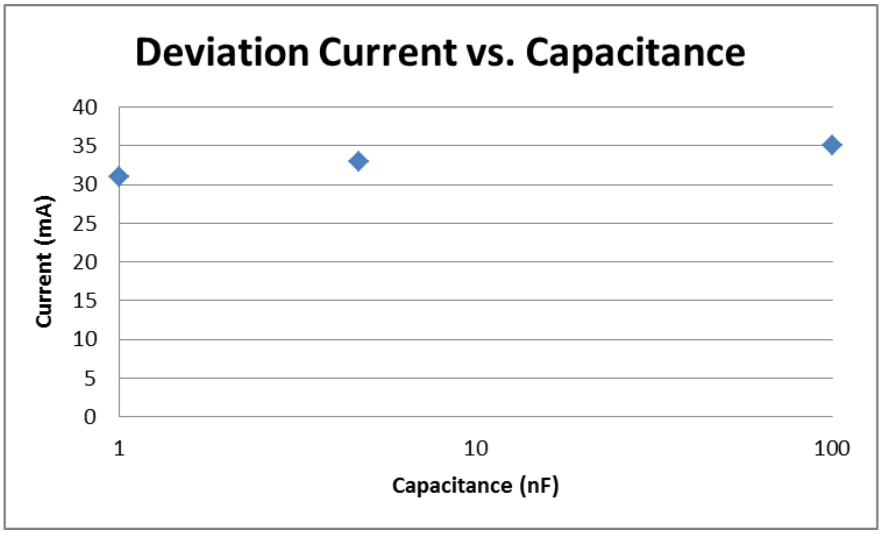
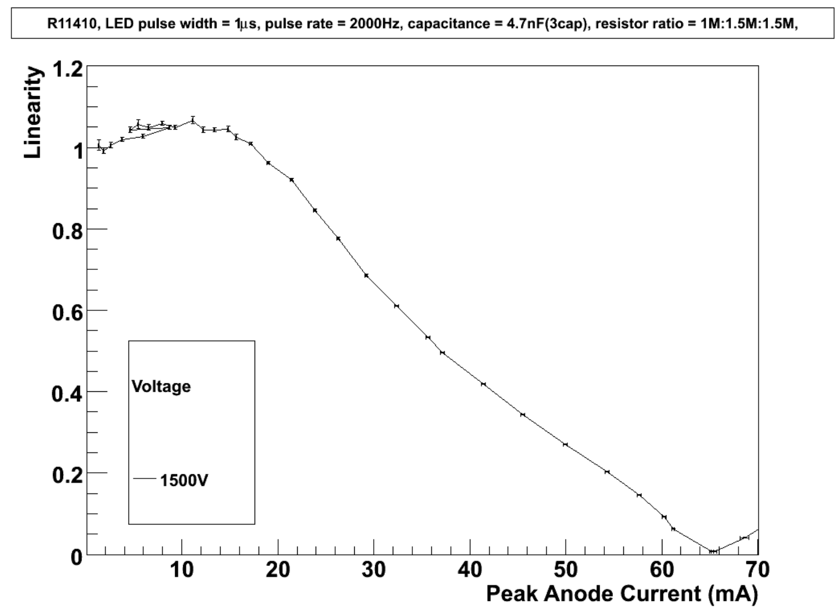


Figure 6: On the Y axis is the current at which the PMT deviates from linearity by 5%. The X axis has the capacitances scanned, 1nF, 4.7nF, and 100nF. The X axis is in logarithmic scale.

As shown in Figure 6, changing the capacitance does not significantly affect linearity. Changing the capacitance by a factor of 10 only changes the deviation current by around 4mA. For comparison, changing the resistance by a factor of 10 changed the deviation current by around 30mA. It is good to know that changing the capacitance does not significantly affect linearity because this allows for smaller capacitors to be used in the real detector and thus further reduces the sources of radioactivity.

4.4 Number of Capacitors

As mentioned previously, capacitors are unwanted sources of radioactivity. Therefore, reducing the number of capacitors is useful. However, because the circuit is deigned to run with four capacitors, changing this number could cause other unwanted effects. Still, it is important to check how changing this number will affect the overall linearity of the system. Originally, four capacitors were used. This number was changed to three and two.



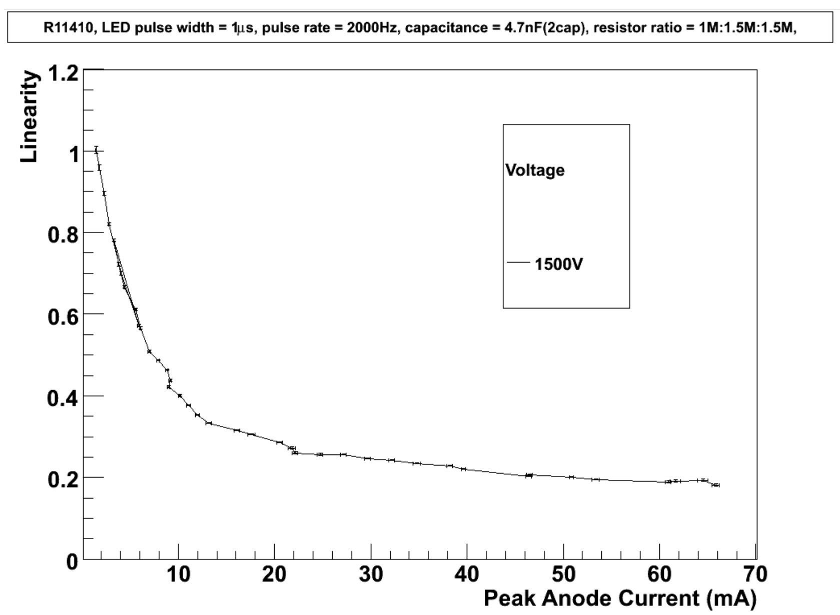


Figure 7: Top- Linearity graph for 3 capacitors. Bottom- Linearity graph for 2 capacitors

As seen in Figure 7, the behavior observed when reducing the number of capacitors is quite strange. It is difficult to give an estimate as to the deviation current, because the behavior exhibited is not similar to the standard operation. However, conclusions can still be reached. Even though no precise deviation current can be pointed to, it is clear that operating with less than four capacitors is not possible under the current conditions.

4.5 Trigger Frequency

Changing the trigger frequency helps to estimate the ability of the PMTs to collect signals at different rates. In the actual detector, the maximum rate at which signals will enter the PMT is around 1000Hz. This is during the calibration of the detector. However, it is still important to understand how linearity is affected at higher frequencies.

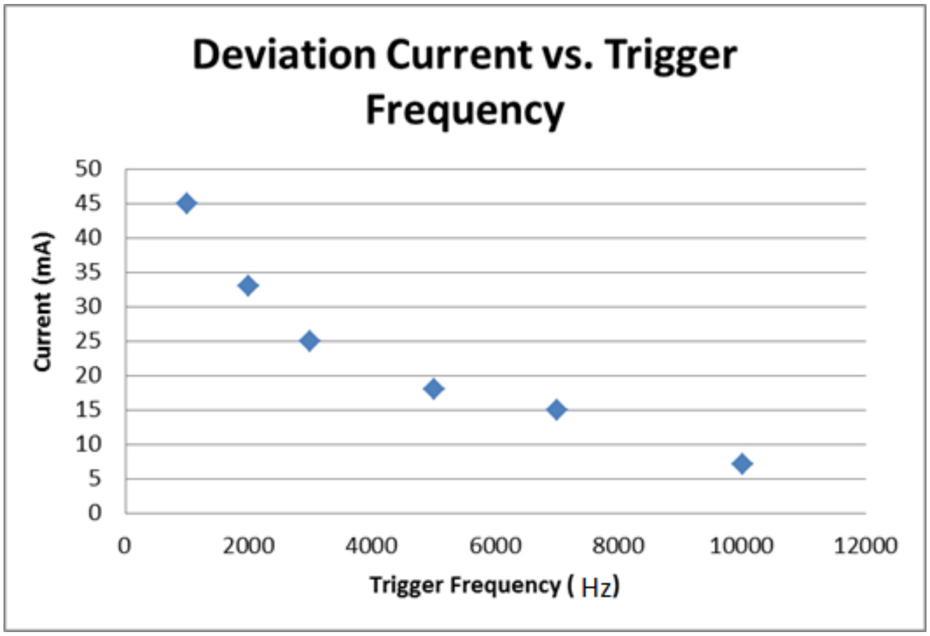


Figure 8: On the Y axis is the current at which the PMT deviates from linearity by 5%. The X axis has the frequencies scanned: 1000Hz, 2000Hz, 3000Hz, 5000Hz, 7000Hz, and 10,000Hz.

As seen in Figure 8, linearity has a strong rate dependence. At 10,000Hz, the deviation current is around 7mA, while at 1000Hz, the deviation current is 45mA. This is good news because the detector will be operating at frequencies of 1000Hz and lower. It is not possible to completely control the rate at which particles enter the detector, but it is sufficiently low that this rate is not a concern for the linearity of the PMTs.

4.6 Base Design

The base of the PMT was also redesigned to reduce sources of radioactivity. The radius of the base was decreased from 50mm to around 36mm. The diameter of the inner hole was increased to 9mm. Lastly, the board thickness was reduced. All of these changes serve to limit the amount of radioactive materials inside the detector. In the Xenon1T experiment, there will be over 250 PMTs inside the device. Because there are so many, reducing even a small amount of material in the base is beneficial to the overall reduction of background in the detector.

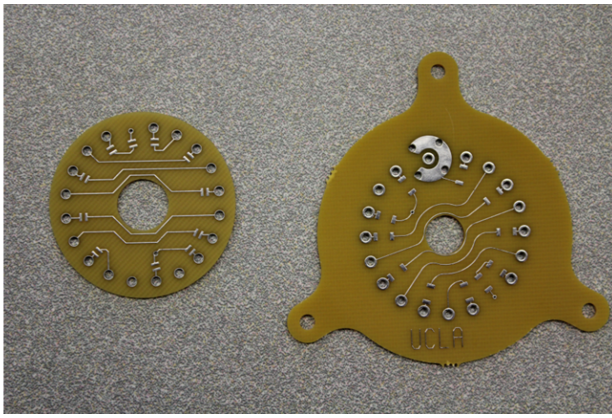


Figure 9: Right-Old Base. Left- New base

5 Discussion

It is important to remember how all of these parameters scanned relate back to the real Xenon1T detector. While ideally, one could simply select the best configurations for the real detector, there are many other concerns. For instance, while it may be beneficial to the linearity of the PMT to reduce the resistance, this is not possible in the real detector. This is because power consumption and funding is a big concern. Other concerns are things like radioactive sources, gain, and heat production. For this reason, it is not a matter of simply selecting the parameters which produce the best linearity. From here, two things must be done. First, more parameters must be scanned. The better the Xenon collaboration understands the behavior of these PMTs, the better they will be able to optimize the new detector. Second, the Xenon collaboration must use these results to optimize the base of the PMT taking into account all of the other considerations for the experiment as a whole.

6 Acknowledgements

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