Constructing and Testing a Cherenkov Particle Detector for Nuclear Physicists at Jefferson Lab

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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Abstract

This report discusses the progress made with the GRINCH (Gas Ring Imaging Cherenkov.) Recent improvements have been made to the alignment system of the mirrors inside the detector to account for extreme angle particles. Wavelength shifting paint was considered as a means to increase the efficiency of the photomultiplier array on the detector. The paint was tested and found to be not dependable as a means of increasing the detector's efficiency.

Introduction

The GRINCH Detector is being constructed for nuclear physicists in Hall A of Jefferson Lab in order to do a better job of detecting electrons in a high background environment than the current Cherenkov detector. In Hall A, there is plenty of background that the detectors are subject to. The current Cherenkov detector consists of 20 five inch photomultiplier tubes. The GRINCH detector consists of an array of 510 photomultipliers, each of which are one inch in diameter. An illustration of how these photomultipliers will be arranged on the detector appears below in Figure 1. Smaller photomultipliers enable the detector to withstand the environment that includes a high rate of background particles and a low rate of particles that it is intended to detect. The current detector with its large photomultiplier limits the intensity of the incident electron beam, as it is easily saturated by background particles. This saturation is avoided by operating the beam at lower intensities. The GRINCH detector, conversely, will allow for a higher intensity of the incident beam, as its array of smaller photomultipliers can withstand a higher event rate before saturating.

The photomultipliers eject an electron when a single photon encounters its cathode, due to the photoelectric effect. This electron then sets off a series of amplifications, which produce an analog current that signals a photon event occurred. The probability that an incident photon motivates the ejection of an electron is the quantum efficiency. This concept of efficiency is discussed at greater length below.

In order to ensure that the incident particles hit the target that is the photomultiplier array, four mirrors with an adjustable radius face the entry envelope of the detector. An illustration of the mirror system is shown below in Figure 2. The mirrors have two degrees of freedom for alignment. Either the radius can be adjusted to increase or decrease the width of the incident zone at which the particles land, or they can be moved towards the envelope or away from the point of entry as a means of shifting over the incident zone. This second degree is to be avoided, as the closer the mirrors are moved to the point of entry, the fewer Cherenkov events there are to detect. The importance of the mirror system is that it ensures that we can maximize the number of good particles seen by the photomultiplier array.

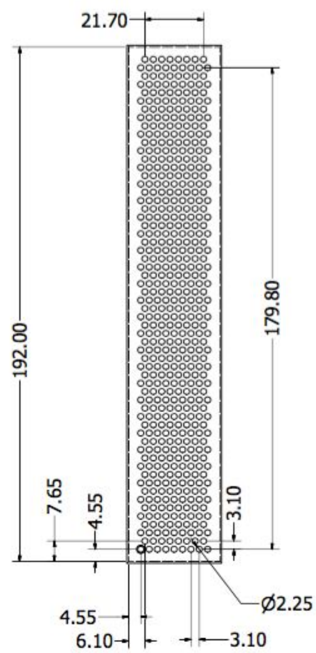

Figure 1. Photomultiplier array on the GRINCH illustration, with measurements in centimeters.

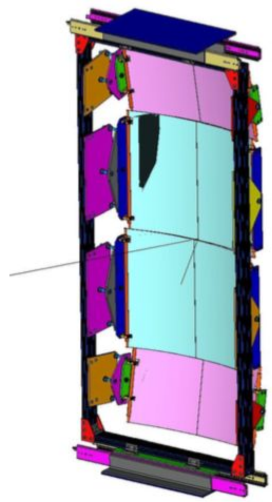

Figure 2. The mirror system that faces the point of entry of the GRINCH. The mirrors reflect the photons from the point of entry towards the Photomultiplier array.

Another important piece of the GRINCH's function is its data acquisition system. The Photomultipliers only produce a small analog output for each photon event. This output will then have to travel over several hundred feet of wire. To ensure that this event is recorded, the photomultiplier signal is fed through a NINO card, which generate a digital signal, which is more likely to be successfully transferred through the wires. The NINO cards send out their digital signal any time the photomultiplier produces an output over a threshold setting. This digital pulse is then analyzed and used to create a histogram of the photomultiplier events over time.

The GRINCH is to be a gas-tight and light tight detector, as part of an attempt to limit the already high amount of background particles. The detector will be sealed with flexible epoxy, so that it will avoid cracking when the detector is moved. Much of this work has already been completed before I began working on the GRINCH, and it will be finished once the mirrors are in place, aligned, and the photomultiplier array is ready to take data.

My work on the GRINCH detector has largely been with regards to investigating the efficiency of the photomultiplier array and testing to see if it can be increased, working on the mirror alignment to ensure that the maximum number of particles reach the photomultiplier array, and assembling the photomultiplier array.

Theory

The GRINCH detector aims to detect the electromagnetic radiation known as Cherenkov radiation. Cherenkov radiation is emitted when a particle travels faster than the speed of light in a medium. This radiation is emitted in a cone, and its is given by:

$$\theta_c = cos^{-1}(\frac{1}{\beta n})$$

Where β is the velocity of the particle divided by the speed of light and n is the refractive index of the medium.

The number of photons emitted via Cherenkov radiation for varying wavelengths is given by:

$$\frac{\partial N}{\partial x} = 2\pi\alpha(1 - \frac{1}{\beta^2 n^2})(\frac{1}{\lambda_L} - \frac{1}{\lambda_H})$$

Where N is the number of photons emitted per distance travelled x, λ_L and λ_H are the minimum and maximum wavelength, and α is the fine structure constant.

Cherenkov detectors use the index of refraction as a means of controlling which particles emit Cherenkov radiation. By setting the index of refraction inside the detector to a specific value, only particles above a threshold velocity will emit Cherenkov radiation. The GRINCH detector's sought after particle is the electron, which has a smaller rest mass than the background particles that are present in Hall A. By manipulating the pressure, we can set the index of refraction inside the GRINCH to be at a point such that electrons will be fast enough to create Cherenkov radiation, but background particles will not. Thus, the photomultiplier array will be able to operate in a high background area without being saturated.

Wavelength Shifting Paint

Photomultipliers' quantum efficiency varies based on the wavelength of the light it is collecting. The photomultipliers that we will be using with the GRINCH, have an efficiency with respect to wavelength shown in figure 3 below:

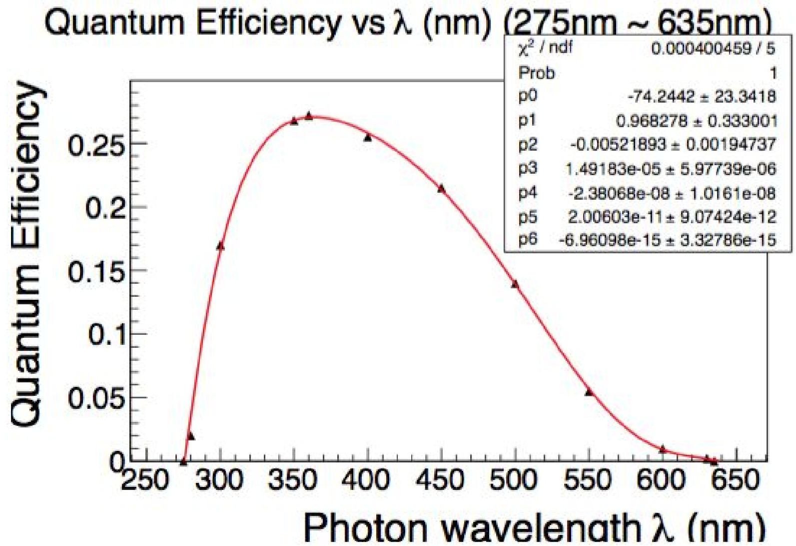

Figure 3. Quantum efficiency of photomultipliers vs. wavelength. The red line is a fit.

For wavelengths of 270 nm and lower, the photomultipliers are ineffective, and they peak at about 350 nm. Clearly, they are incredibly sensitive to the wavelength of the photons they are detecting.

Unfortunately, Cherenkov radiation generally emits photons at lower wavelengths than accepted by the photomultipliers. A plot of the Cherenkov spectrum is seen below. For convenience, the efficiency of various photomultipliers for varying wavelengths is seen on the same plot.

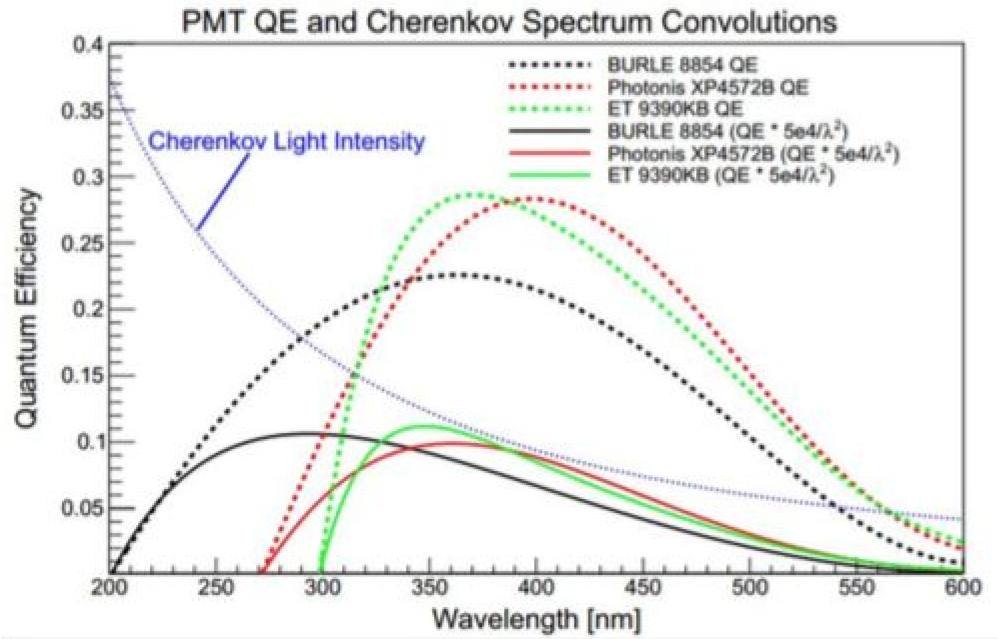

Figure 4. Cherenkov spectrum compared with various photomultipliers' efficiency. The green dotted line (ET 9390KB) is identical to the efficiency of our photomultipliers. The Cherenkov intensity line is plotted as wavelength against number of photons in arbitrary units.

As clearly shown in the above plot, Cherenkov light is most intense in the UV spectrum, and drops off as the wavelength increases. At the wavelength that our photomultipliers start detecting, the Cherenkov light is only half as intense as it is a 200 nm wavelength. This phenomenon means that our detector is incapable of detecting much of the Cherenkov light present, greatly reducing the number of incidents measured.

The effectiveness of the GRINCH would be greatly increased if there was a way to shift the more intense wavelengths of the Cherenkov spectrum to the wavelength at which our photomultipliers are most efficient at detecting. Supposedly, this process is made possible by wavelength shifting paint. I tested various samples and thicknesses of this paint in order to see if could in practice shift the intense wavelengths of Cherenkov light into the detectable region of our photomultipliers.

Experimental Setup

The two most important pieces of testing the wavelength shifting paint's effectiveness were a stable UV light source and a spectrometer that would be accurate down to 200 nm wavelengths. We acquired a Deuterium lamp, a power supply, and a spectrometer sensitive between about 150 nm and 1200 nm. The Deuterium lamp produced light between 200 and 800 nm. It produced very bright light in the visible region (a large peak at about 650 nm) but more importantly for this experiment, it produced a stable amount of light in the UV range, peaking at about 250 nm. This UV light would simulate the Cherenkov light. If the paint could absorb some of this light and re-emit it at a higher wavelength, then it would be useful for the phototubes in the GRINCH detector.

Once the above materials were acquired, the next step was to set up the experiment so that we could easily swap painted disks in and out, while avoiding any change in background noise. We designed a simple set up in which the spectrometer was aimed at the lamp and as close to it as possible without becoming saturated. In between the lamp and the spectrometer stood a holder for a lens, which could easily be swapped out to see the lamp's spectrum without any interference, a spectrum through a blank lens, or a spectrum through a painted lens.

Potential problems were ambient light, the lamp's stability as it remained on for close to an hour, and if a blank lens had any impact on the light entering the spectrometer (other than slightly diminishing it in a uniform matter.) All of these considerations were tested for, and the results were as follows: Ambient light had minimal impact on the set up. Whether the lights were on or off, the spectrometer gave similar readings. This result was true both with the lamp on or with the lamp off. The spectrometer had a very small opening in the optical fiber, which only picked up a spectrum when it picked up intense light directly aligned with it. As for how the lamp operated over time, it turns out that it actually produced slightly more intense light after about thirty minutes, however it was a negligible increase. As expected, a blank lens, which would be replaced with a painted lens later in the experiment, did not change the shape of the spectrum, instead it just barely diminished the intensity.

Results

The first testing of the wavelength shifting paint yielded disappointing results. The paint was expected to absorb the light in the UV range and re-emit it at a higher wavelength, but as figure 5 shows, it successfully absorbed the UV light, but it did not effectively re-emit it at any point on the spectrum.

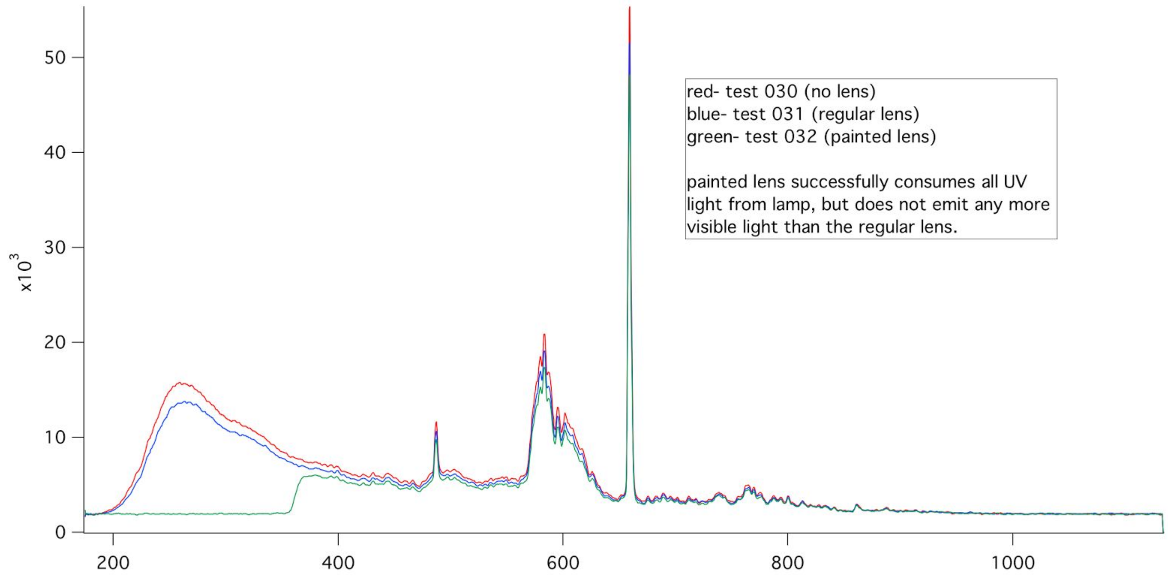

Figure 5. Initial wavelength shifting paint test, plotted as wavelength against intensity of light. Each spectrum is labeled in the legend.

The best explanation for the above result is that the paint is re-emitting the light, but it's not making it to the spectrometer. This seems plausible as the paint is clearly working in some way, as it discriminatorily absorbs all of the light up to the 300 nm range. After that it acts in a similar manner to the blank lens, in that it only slightly diminishes the light intensity, without changing the shape of the spectrum. This idea of lost light is further plausible due to the fact that the lens was a few inches away from the spectrometer and as discussed above, the spectrometer is only sensitive to direct light. In the following experiments, the lens was as close to the spectrometer as possible, which mimics where the paint would be in relation to a photomultiplier.

Another issue to be considered is that the paint we were using might have gone bad, or in some way became less effective than it once was. Furthermore, there could have been something wrong with the method we were using to paint the disks. To see if either of these had an effect, we acquired a new sample of the paint and we acquired the painted lenses that were used in a previous experiment by Scott Barcus. With this new material acquired, we tested the old paint, the new paint, as well as the old lenses. We also took one measurement of a lens with a thinner coating, as the batch of old lenses had varying amounts of paint thickness. The results can be seen in the following plot:

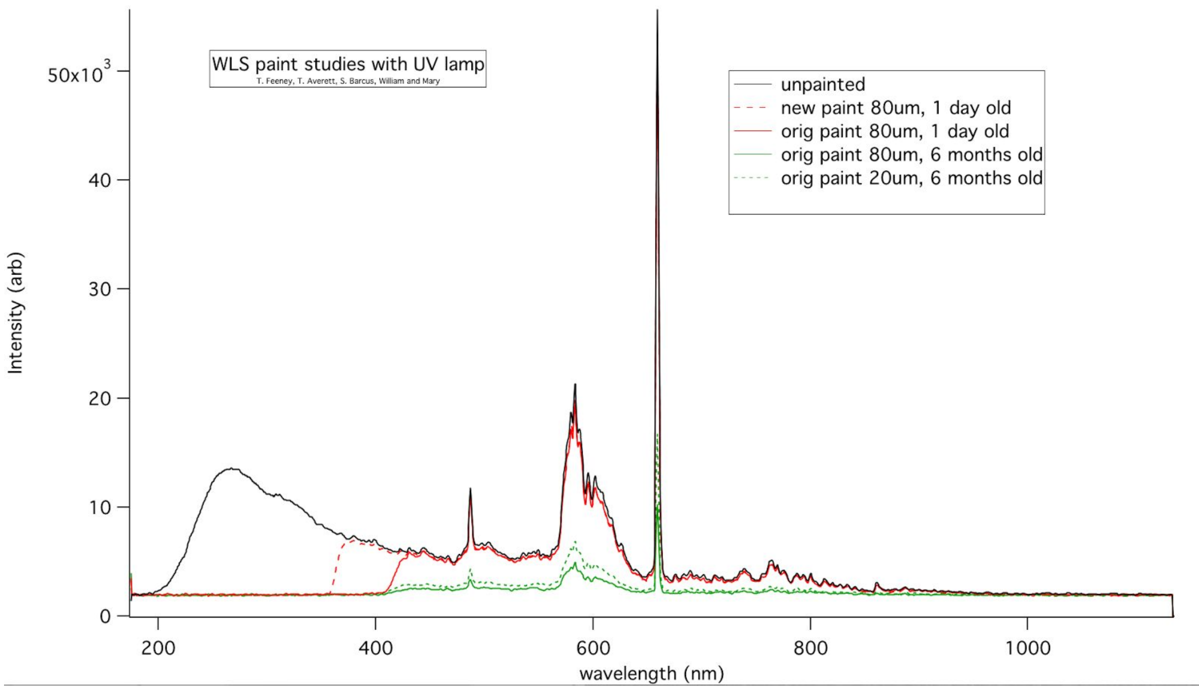

Figure 6. Wavelength against intensity plot comparing old lenses, new lenses, old paint and new paint, and paint thickness.

There are plenty of different variables in the above graph, but the result is clear from all of them. None of them increase the light detected by the spectrometer at any point on the spectrum. Most of them continue absorbing light past the peak efficiency of the photomultiplier. Regardless of the age of the paint, the age of the disks, or the thicknesses tested, the paint absorbed UV light efficiently, but failed to increase light at higher wavelengths.

Shown below is a picture of the disks against a mirror. The picture provides a good reason as to why the disks failed to re-emit light.

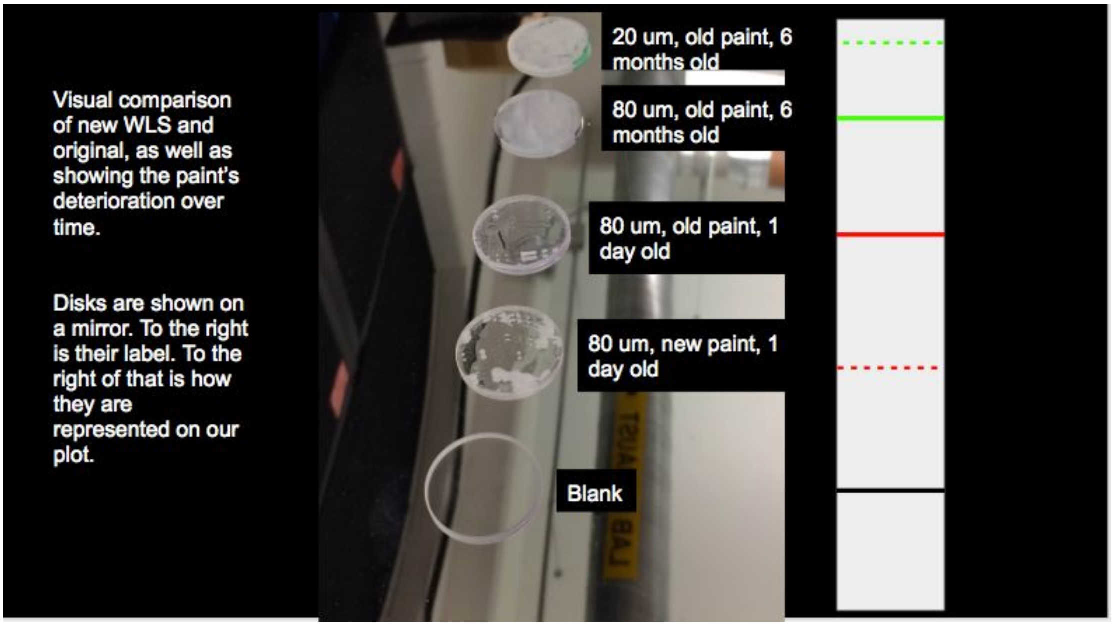

Figure 7. An image of the disks used in the above experiment.

The disks are at best, splotchy, and at worst, opaque. This visible obstruction hints at why the disks fail to increase the intensity of the spectrum at our targeted wavelengths. There seems to be a correlation between age and opaqueness. This correlation suggests that the paint crystallizes when left on the glass over time, which would be very bad news considering the expected lifetime of the GRINCH. A quick inspection with a magnifying glass showed that the paint is indeed crystallizing on the surface.

The one thing left to test in this system is the thickness of the paint. So far, we have tested samples from 20 µm and up. The most efficient thickness could potentially be at much thinner. A paper by researchers from Temple University working at Jefferson lab showed that a very small amount of wavelength shifting paint, applied via vapor deposit, successfully increased the wavelength of incident light (S. Joosten et. al.) This increase in wavelength came without the drop off intensity with which we struggled. We estimated that the vapor deposit system applied paint to the lenses with a thickness on the order of a single micron.

A plot of our thinly painted lens test is shown below. The results are similar to what we saw with the thicker lenses.

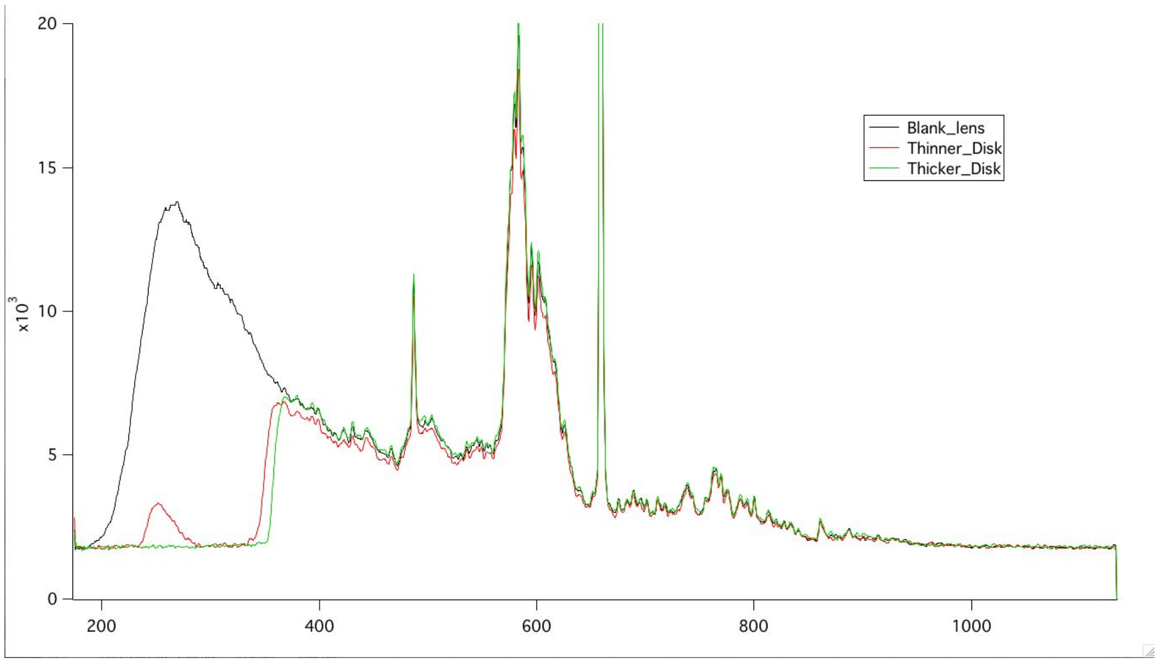

Figure 8. Testing a thinner amount of paint. The x scaled represents wavelength of the light, as the y scale represents intensity of the light. The y scale here is slightly different than the previous plots, as we allowed the spectrometer to saturate at the peak at 650 nm, as we were not concerned with this range.

The results here are similar to the results of the previous tests. Painting the disk as thin as we possibly could did not enable it to re-emit light any better. The bump around 220 nm is evidence that when painting at this minimal thickness, we are not able to do so uniformly. Regardless of that, the paint continued to fail at increasing light in the photomultipliers' most efficient wavelengths.

Clearly, the wavelength shifting paint is not an effective tool for increasing the incident photons in the photomultipliers' peak efficiency wavelengths. In most cases, the paint actually continued absorbing light at wavelengths that the photomultiplier would be measuring. Taking these results as a cue, we will not be moving forward with wavelength shifting paint during this project.

Mirror Alignment

There is much less to be said about the mirror alignment process than the wavelength shifting paint experiments, as there is no experiment to be done here. We worked to ensure that the mirrors reflected the maximum number of particles onto the photomultiplier array. We actually over adjusted for particles when possible and aimed to get the most extreme particles to hit within an inch inside of the array's border.

The angles of particle entry were taken from a simulation ran by cooperators at Jefferson Lab. Below is the plot that we used:

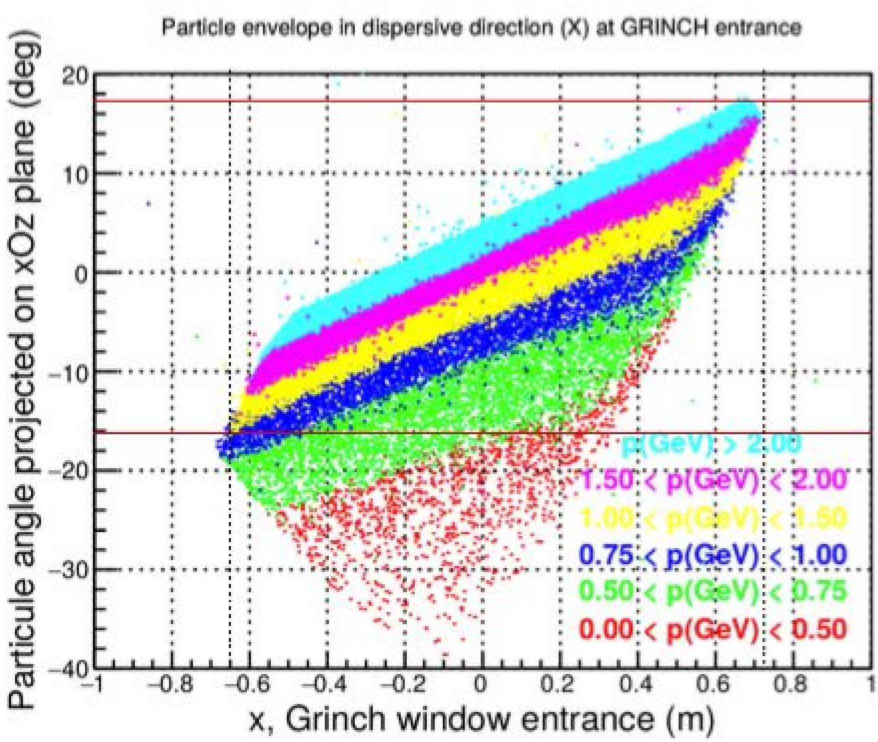

Figure 9. Resulting plot from particle entry simulation. The red line dictates the angle of the maximum angle of the extreme particles.

To simulate the particles entering the detector and how they would be reflected by the mirrors, we used a laser beam mounted on a sliding system. This system allowed us to move the system horizontally across the detector and see how the light was deflected at different points. We checked all possible angles listed in the plot above on all four mirrors. The alignment of the mirrors is not completed yet but should be in the near future. It looks like we will be able to direct all of the particles entering the detector onto the photomultiplier array, which will be a success for ensuring the detector's efficiency.

PMT Preparation and Assembly

As mentioned above, the phototube array accommodates for 510 one inch PMTs. James Madison provided Jefferson Laboratory with enough PMTs for the detector. The PMTs were labeled by number and the gain of each was accounted for.

The GRINCH will be a gas tight detector, so each PMT must be sealed into the detector. To achieve this, we placed two 2mm O-rings on the PMT – one on the side pressing up against the inside of the detector, the other pressing against the outside of the detector. The inside O-rings were placed on the PMT prior to assembly and during the same process we cleaned the PMTs to ensure that dust would not be an issue. The second O-ring was placed on the PMT when it was fastened to its position on the detector. The O-rings were secured with the copper rings that screwed the PMT into their positions.

Ideally, this arrangement will prevent leaks in the 510 holes that hold the PMTs. The inside of the detector will be at a pressure slightly higher than a standard atmosphere.

The detector has its own magnetic field, which means the rotational placement of the PMTs is a factor. In order to maximize the photons they detect, we must place them such that the detector's magnetic field does not interfere with the electron travelling through the PMT. Ensuring this alignment was the crux of placing the PMTs in their positions.

The PMTs were given to us labelled by number. JMU provided us with the measured gain of each PMT, and a list of where they each were to be placed in the array. Placing the PMTs in correspondence with this list ensures smoother function of the DAQ during operation, as the gain of each will be known in conjunction with its position.

To maximize the amount of light that makes it to the PMTs, we installed a light catcher on each row. This reflective surface filled the gaps between the PMT's and reflects light towards them.

Figure 10. An angled view of the light catchers and the PMTs

Conclusion

During my time on the project, we have gathered data to show that the wavelength shifting paint is not a practical means of increasing the photomultiplier tubes' efficiency, we made progress in the alignment of the mirror system and we prepared and assembled the PMT array. Future work will include finishing the mirror system alignment, sealing the detector with epoxy, and making sure that the data acquisition system is prepared to amplify and measure the photomultipliers' small analog output at each event.

References

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