Characterization of $PbWO_4$

Christian Runyon

Abstract:

All visible matter in the universe is made up of the subatomic particles quarks and gluons. In order to further understand their behavior, the Jefferson Lab (JLab) conducts various experiments using their Continuous Electron Beam Accelerator Facility (CEBAF) which smashes electrons at practically the speed of light into various targets. The lab lacks a high moment, high precision detector which can detect neutral particles. The Neutral Particle Spectrometer (NPS) is a crystal electromagnetic calorimeter preceded by a sweeping magnet to sweep away charged particles. It will be built at the JLab from 2015-2018. In this paper I will show the results of $PbWO_4$'s crystal quality studies for use in the NPS. $PbWO_4$ is optimal for the NPS due to its small Moliere radius, which greatly increases precision, and radiation hardness, keeping the crystal intact after showers of high energy particles. The critical aspect for crystal quality, and thus resolution and precision, is the combination of high light output and, as stated, the radiation hardness, both of which depend strongly on the manufacturing process. I have tested the performance of $PbWO_4$ crystals, and in particular, measured their light yield, optical transmittance, and refractive index. The homogeneity of the crystal was investigated based on the variation between these optical properties.

Introduction:

This project was conducted to test the uniformity and homogeneity of lead tungstate, a crystal to be used in an electromagnetic calorimeter at the JLab. The detector will contain ~1100 crystals which $PbWO_4$ (see figure 2) is a dense scintillating crystal that, due to its growth method, often varies slightly between orientation and position on the crystal. The crystals which I worked with and which will be used in the detector are $2x2x20cm^3$. They are grown from one end until they are 20cm long giving room for variations as they are grown. It is necessary to understand if

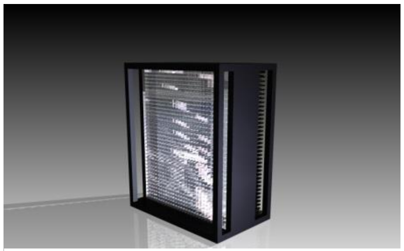


Figure 1: Computer model of the NPS detector, courtesy CUA physics wiki

the crystals vary because, for the calorimeter to provide the needed resolution, the crystals must be homogenous and of good quality. The quality can be tested by investigating various optical properties, such as their refractive index, transmittance, and light yield. The index of refraction is a property of a material which dictates how quickly light travels through that material. As light passes through a material with one index of refraction to a material with a different index of refraction, the light changes speed and "bends" as it changes mediums. When light travels from a material with a low index of refraction to one with a high index of refraction, the light is bent toward the normal, and vice versa. This is important to measure because, even if the crystal is damaged slightly, the refractive index should remain constant. The transmittance of $PbWO_4$ is how much light of different wavelengths can travel through the tile. This is important for understanding if the quality of the crystal meet the requirements for the detector as well as the homogeneity and uniformity. Light yield is a measurement which is defined as the number of photoelectrons per amount of energy. The crystal must especially meet the parameters for the detector in this measurement because it is the mechanism which will be used in the detector. The mechanism of the detector is first, to sweep away any charged particles using a magnet. Next, the remaining neutral particles strike the crystal. Then the crystal scintillates giving off a varied number of photoelectrons based on the energy of the particle. Lastly the number of photoelectrons is measured and this can be used to determine the energy, and therefore identification, of the particle. [1] All of the crystals measured were from the Russian company Bogoroditsk Techno-Chemical Plant (except for the ones label “CRYTUR” which were from the Czech company CRYTUR. Since the crystal varies between orientations and positions, I used several conventions to keep track of orientation, crystal, and position. To keep track of orientation, I put a dot on the corners of each of the faces. To keep track of positions, I always measured from the side OPPOSITE the dots towards the dots. Each crystal had a label on its storage box excluding the Czech crystals. The labels were: ##, 078, 064, and ###. I was not able to take refractive index and transmittance data for crystal ###.

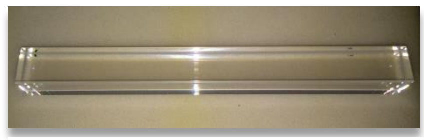


Figure 2: $PbWO_4$

Calculating the Refractive Index:

A picture of the set-up can be seen in Figure 3. To find the refractive index, I developed a method based on Snell's law and some geometry to measure refractive index, and then I built the set-up and took measurements. This setup includes a laser, calipers, a turn table, and graph paper in-line with the desk. I raised the laser a couple of centimeters so that it was at the correct height for the turn table. The crystal was then cleaned and placed on the turntable where a sheet of paper was marked to keep track of position. To find the refractive index I used the following equation: $n = \sqrt{\frac{\sin 2\theta}{2(\sin\theta - \frac{\Delta x}{L})} + \sin^2 \theta}$. This equation was derived using Snell's Law. N is the refractive index of $PbWO_4$. Θ is the incident angle of the laser and the $PbWO_4$. Δx is the displacement of the laser caused by the refraction. L is the width of the crystal. Measurements of the displacement and width were taken using Mitutoyo CD-6" B electric calipers, which can measure the fraction of a millimeter resolution needed. Theta was found by taking a picture of the crystal and then using the image analyzation software Digimizer to calculate the angle.

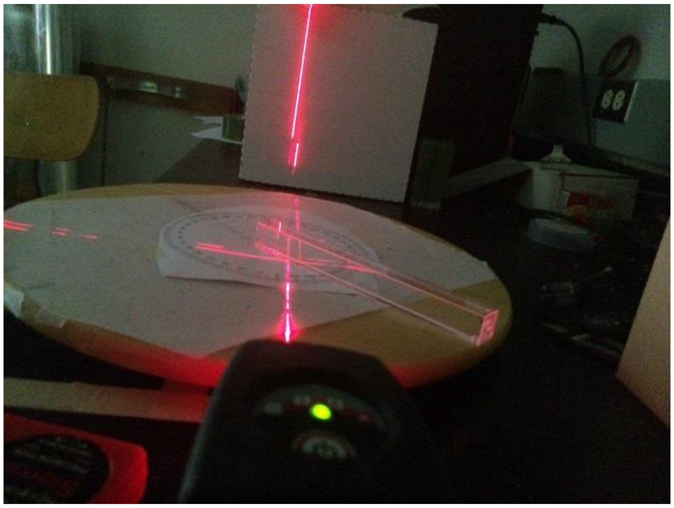


Figure 3: Set up for measuring the refractive index

Measuring Transmittance:

Using a PerkinElmer Lambda 750 Uv/Vis/Nir Spectrometer I tested the transmittance of the aerogel tiles. Due to the large size of the crystal, we had to create a stand for it which would fit inside the spectrometer. A piece of strong Styrofoam with grooves cut into it was used to hold the crystals during measurements. For the measurements, I set the spectrometer to use wavelengths of 800 nm to 250 nm in 1-5 nm steps which. I took measurements through two orientations and along the crystal I then analyzed the data using Excel.

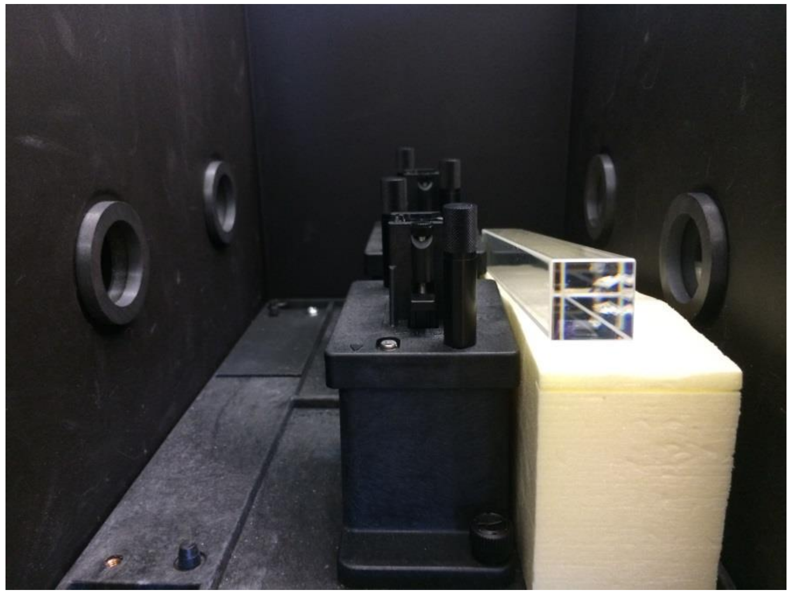


Figure 4: Inside the spectrometer, the far beam is a reference while the closer beam passes through the crystal and measures the transmittance compared to the reference

Measuring Light Yield:

It is know that the light yield of $PbWO_4$ varies with temperature. In order to correct this, I modified a floor freezer so that it could house a setup consisting of a Na-22 source, a Hamamatsu R4125 PMT, a collimator, a plastic scintillator attached to a second PMT for triggering, and an ADC-based readout. Also inside the freezer is a heater, which fights with the freezer

Figure 5: Set up for measuring light yield. The radioactive source is on the yellow styrofoam. The two iron bricks are the collimator. The crystal and PMT are in center back wall. The trigger PMT and scintillator are center front wall. Beneath the setup is the heater and a dehumidifier which stops ice from forming on the walls.

stopping the freezer's periodic shut off at lower temperatures, and a stepper motor. The stepper motor is controlled from outside the freezer using a computer and it creates an easy way to change the position without opening the freezer. Keeping the temperature constant proved to be difficult. When left on overnight, sometimes the freezer would shut off or slow down and the temperature would rise into the 100 degrees Fahrenheit. While taking measurements, keeping the temperature within ~1 degree was also difficult. The fight between the heater and freezer proved it could keep the temperature constant at 50°, but if ever knocked out of equilibrium, the temperature would sometimes rise, sometimes fall. This deviance could arise from opening the freezer for a few seconds, or sometimes happen without notice. To fix this, I would wait twenty minutes and check back, hoping the temper re-stabilized. If it did not, I would shut off either the heater or freezer and then repeat the waiting and checking again. There were two steps to taking measurements. The first was to calibrate the PMT. This was done by pulsing an LED attached to the crystal with one photon. By measuring how the PMT picks up this, we then can know the channel number of the ADC which corresponds to one photon. Secondly, a radioactive source was placed so that it would emit high energy photons into the side of the crystal. Then, by taking the channel number which is picked up from the radioactive source and dividing it by the calibration number, we are given the number of photoelectrons.

Refractive index results:

When calculating the refractive index error, due to the equation being very sensitive even at variations of one tenth of a millimeter, we cannot make any larger conclusions. The measurements support that the crystal is consistent with literature [2], and, within the error, they do not deviate. I took ten data points always through orientation one for each crystal. I did not test different orientations due to the large uncertainty in the measurement. The uncertainty was calculated by first taking each of the three measurements numerous times to discover the uncertainty in those measurements. For the displacement it turned out to be ± .2-.4mm (earlier methods were less exact), for the width it was ±.05mm, and for the angle it was ± .3-.5°. Then, using excel, the highest and lowest refractive indexes based on those uncertainties were calculated. The average of difference between these numbers and the calculated refractive index is the uncertainty.

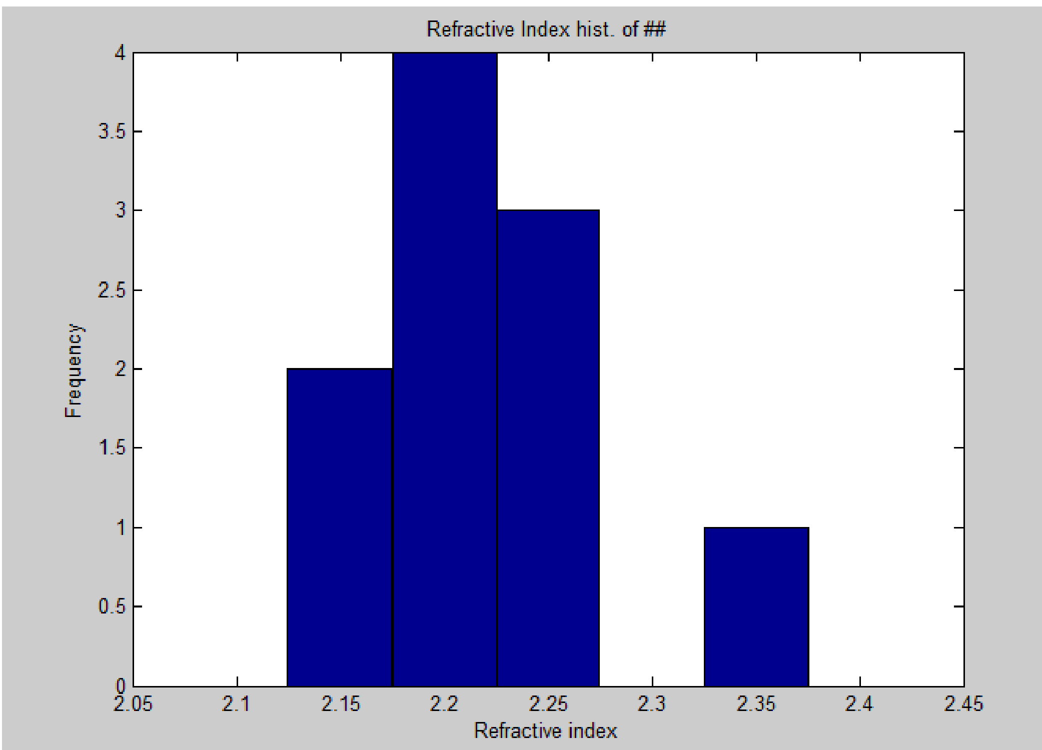


Figure 6: Refractive index histogram of crystal ##. The uncertainty was ±1.5 giving this crystal a refractive index of 2.2 ±1.5 which is consistent with literature.

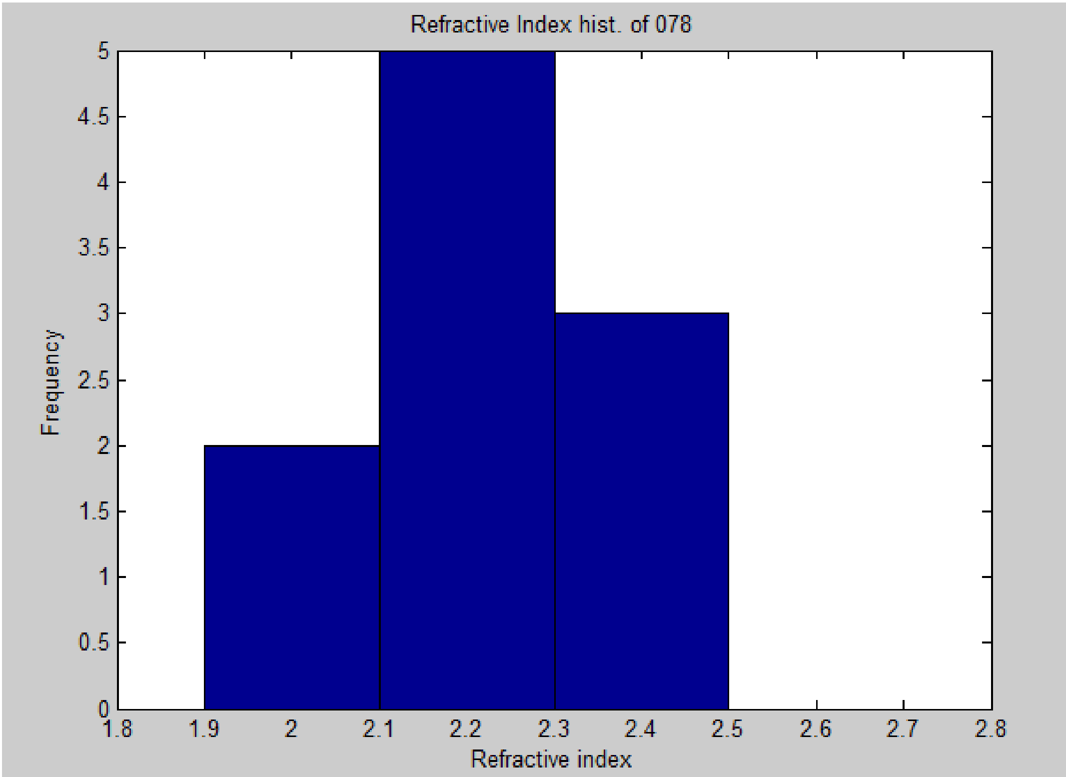


Figure 7: The refractive index of crystal 078. Here the uncertainty is ±2.5. The bins for the histogram are 2.0,2.2,2.4

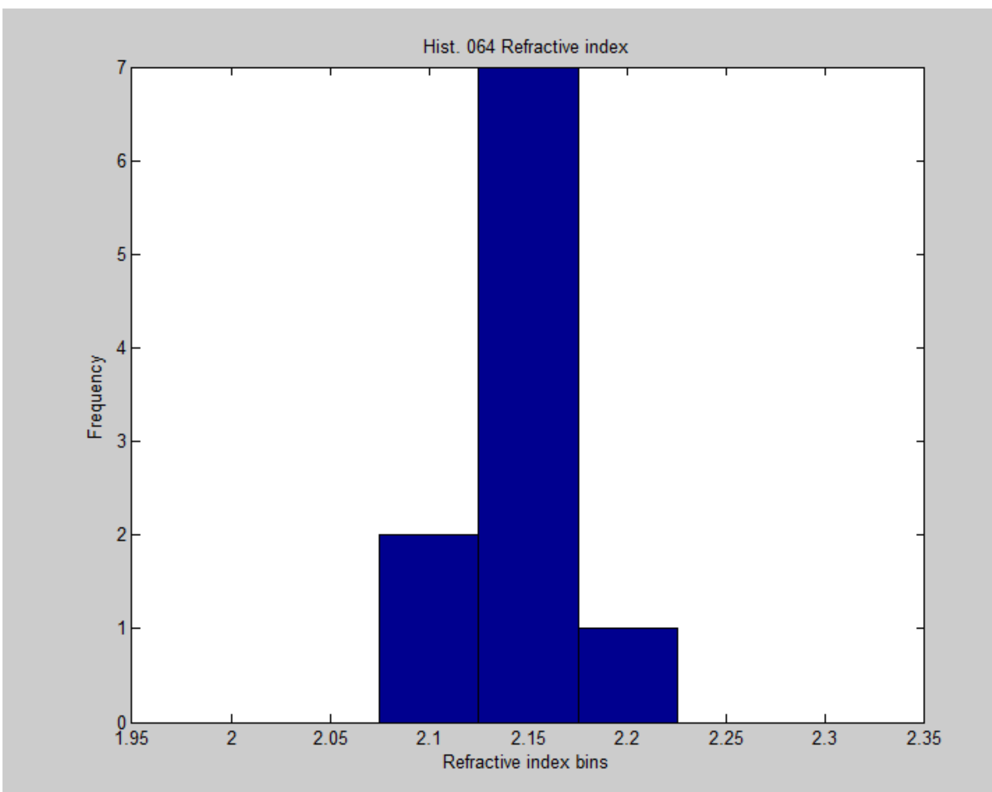
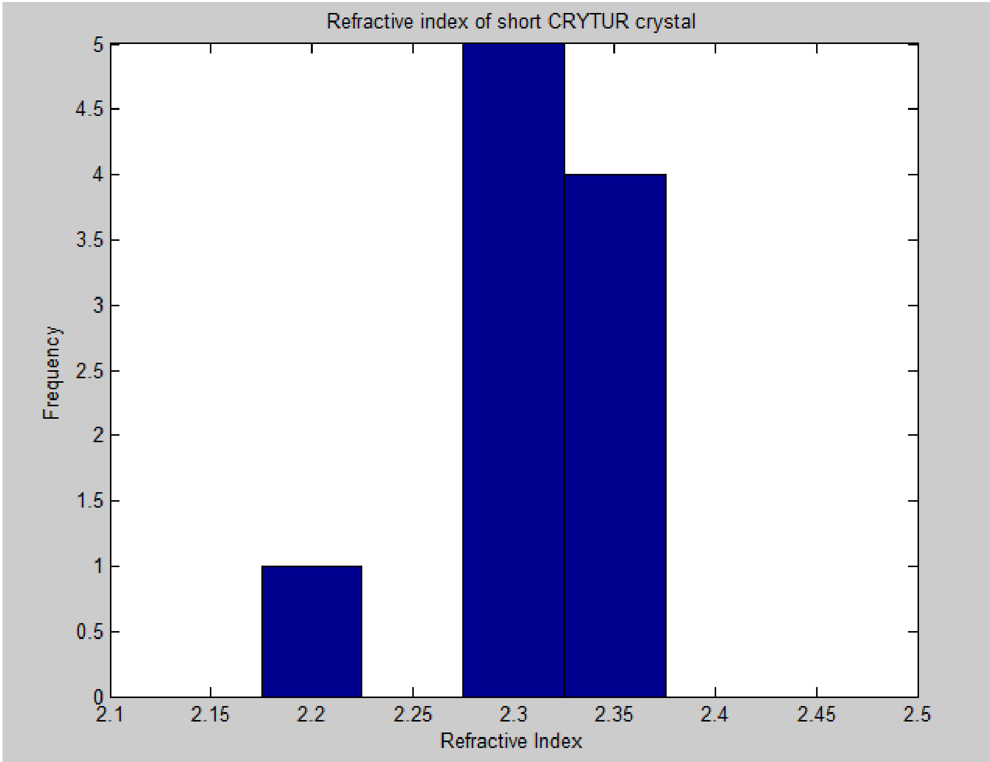


Figure 8: Here are the most consistent measurements. The refractive index appears to be 2.15 ± 1.5.

Figure 9: Refractive index of the short crystal from the Czech company. It has a refractive index of 2.3±1.5.



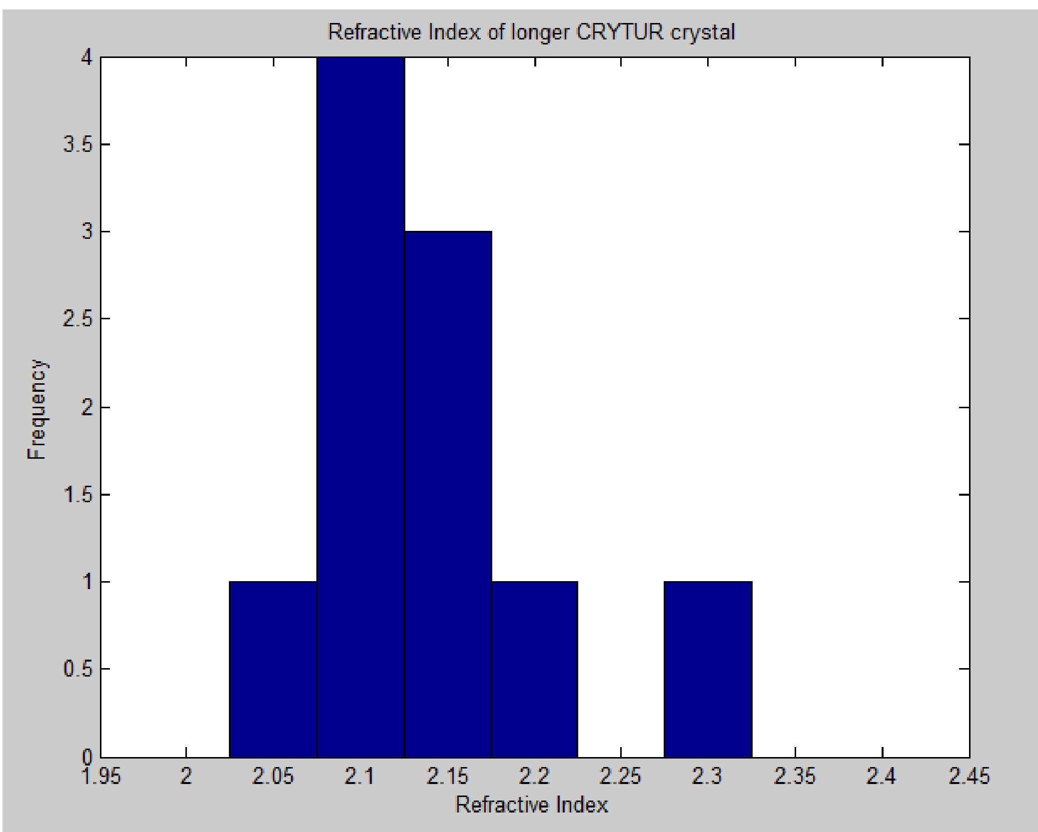


Figure 10: The refractive index appears to be 2.1 for the long Czech crystal. This also showed the least normal distribution of data points

Transmittance Results

The transmittance measurements proved to be fairly uniform. There is variation from crystal to crystal and orientation to orientation. I found that the deviation is ±1.5% and the error of the measurements to be a minimum of ±.1%. Because of the number of measurements and the time it took to take them, the systematic error is more likely ±.3%. Due to this systematic error, it is hard to make conclusions on the uniformity along position; the crystals may vary from one end versus the other, but within the error the data is inconclusive. A setup which could keep the crystal consistently perpendicular to the light beam of the spectrometer is necessary for confirmation or disproval of this hypothesis.

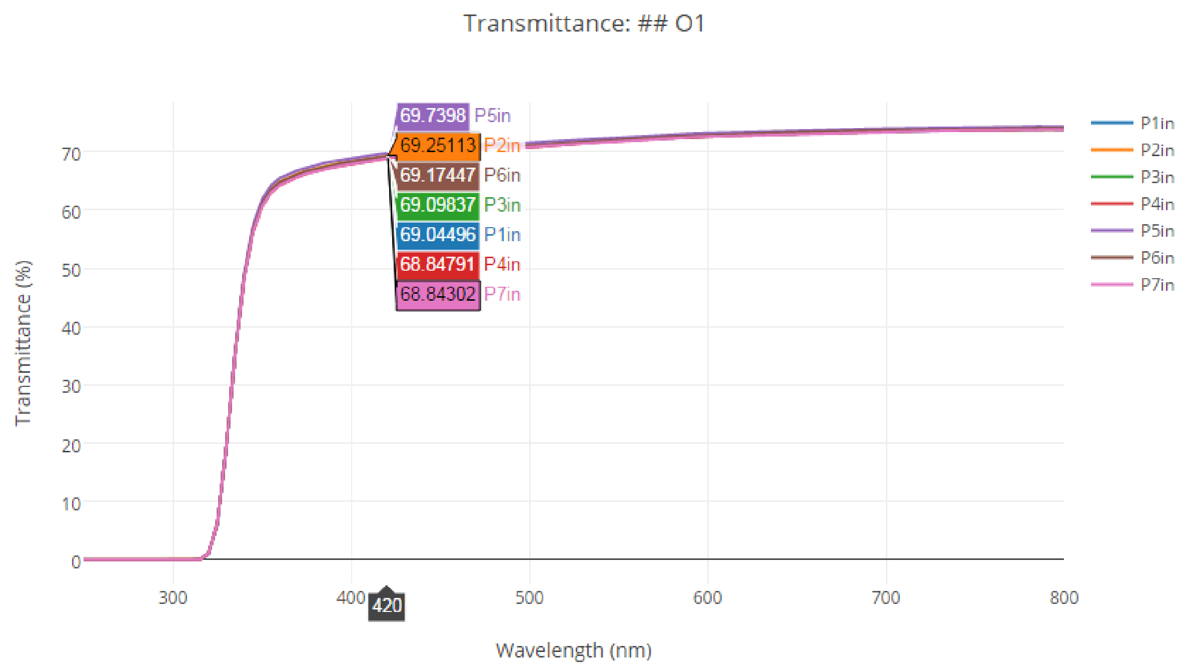


Figure 12: Transmittance of crystal ##, orientation 1. There is about a .5% deviation in the measurements between the positions of the crystal.

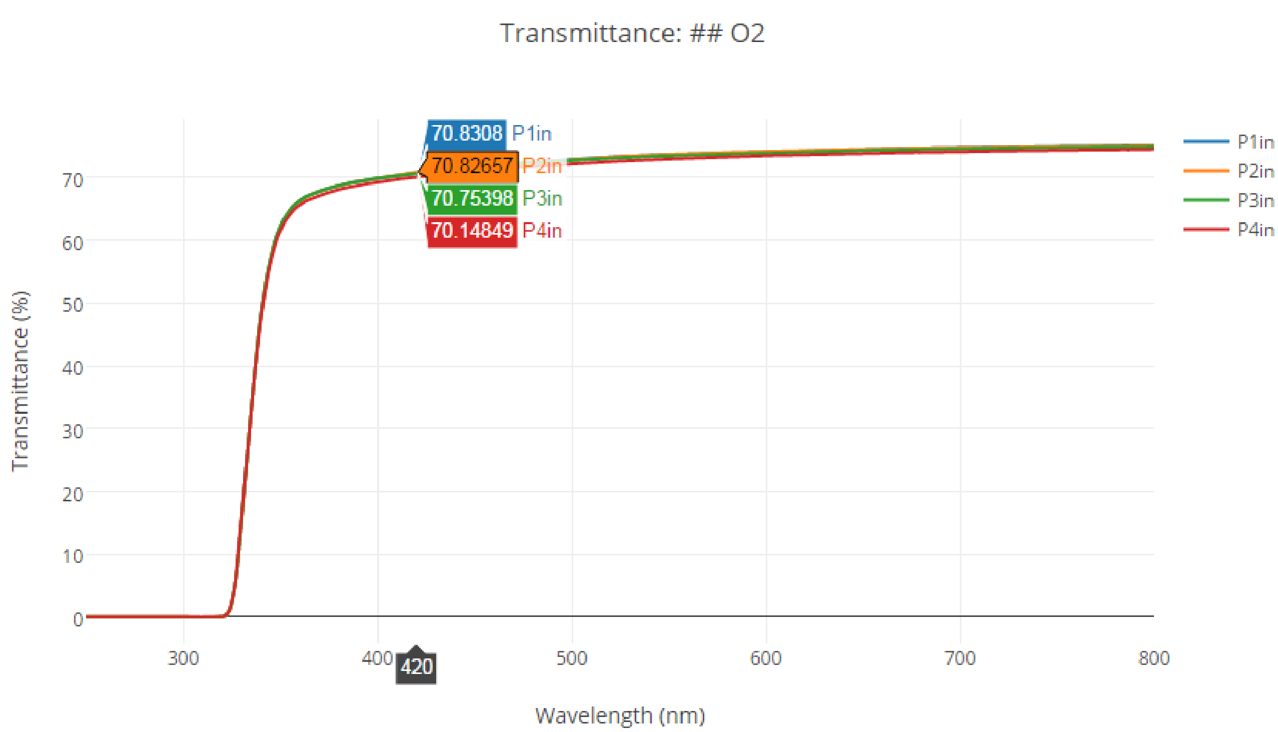
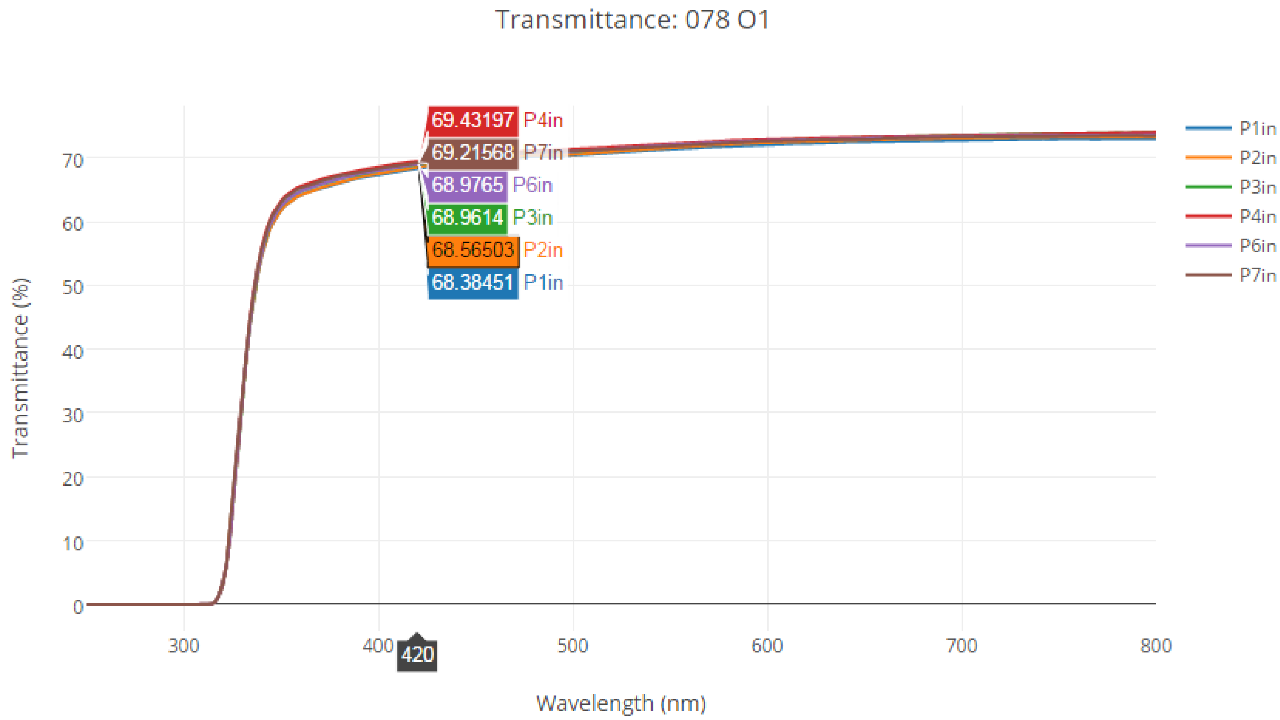


Figure 11: Positions 5in-7in did not get measured for this orientation. This orientation of this crystal also has the highest transmittance of the measured crystals.

Figure 13: Transmittance of crystal 078, O1. P5in's measurement was faulty due to a hiccup with the spectrometer. The transmittances all look on par with the necessary parameters [3] for the NPS



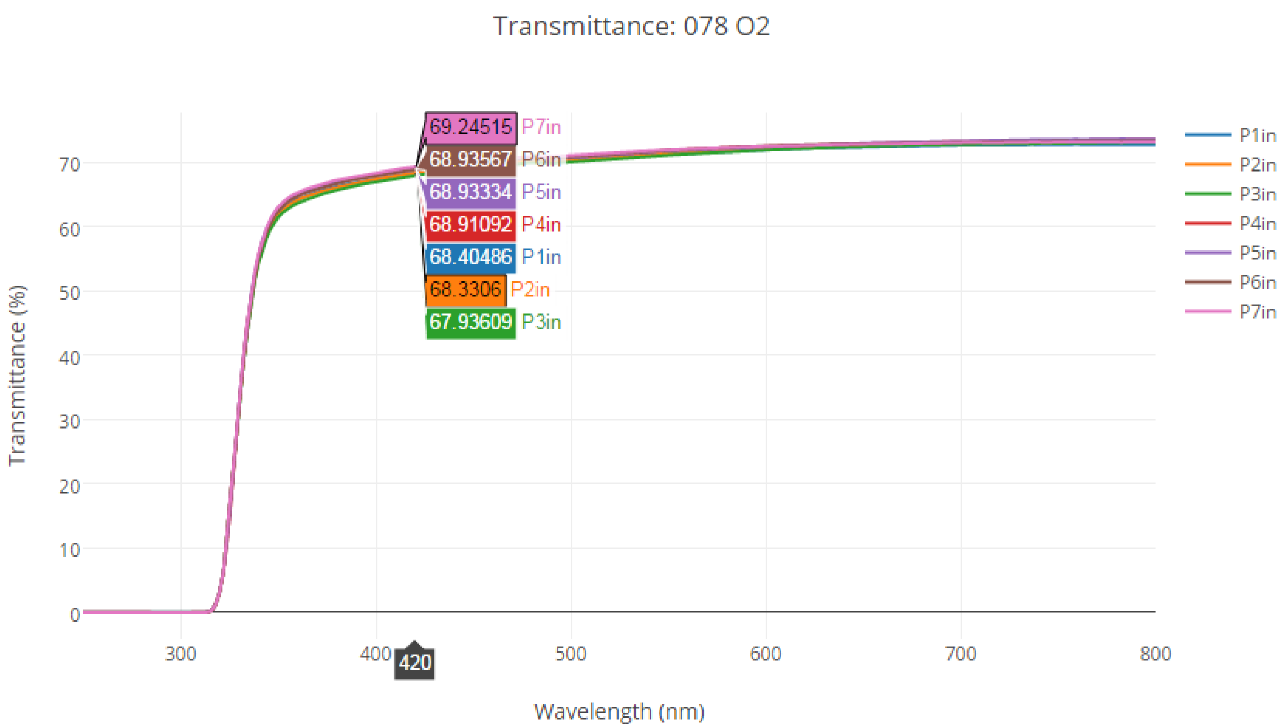
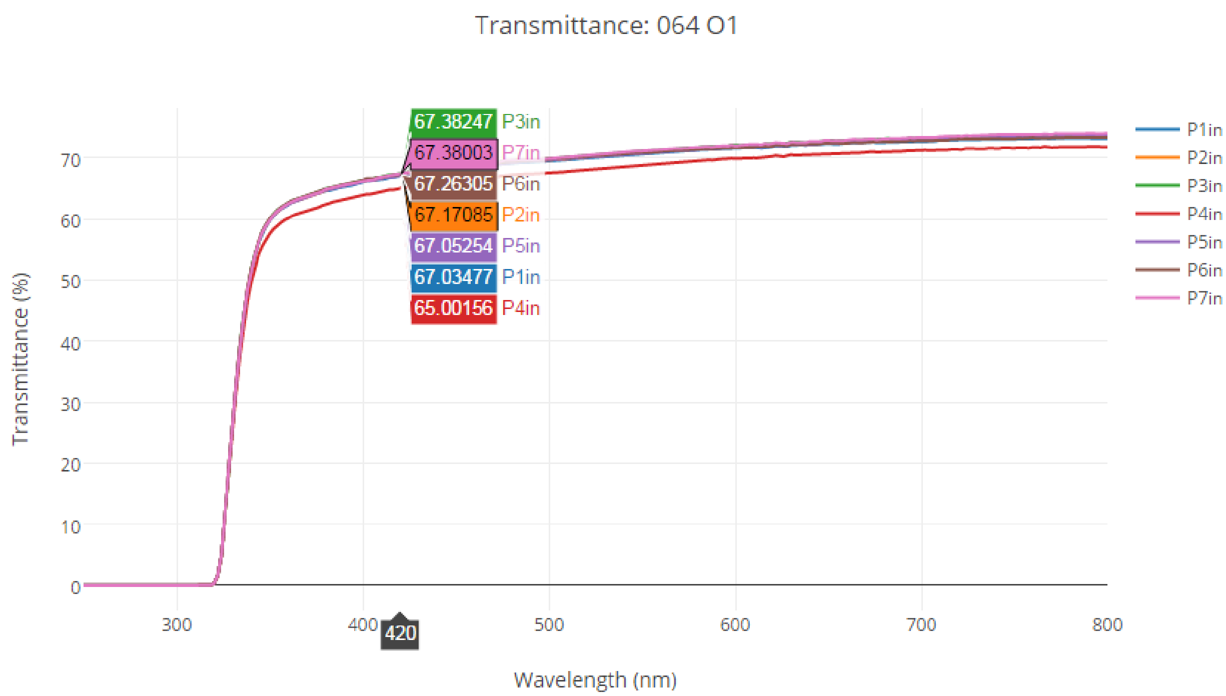


Figure 14: Transmittance of 078 orientation 2, the results here look good

Figure 15: No apparent correlation of transmittance to position here. P4in is a good example of a sloppy measurement due to fatigue.



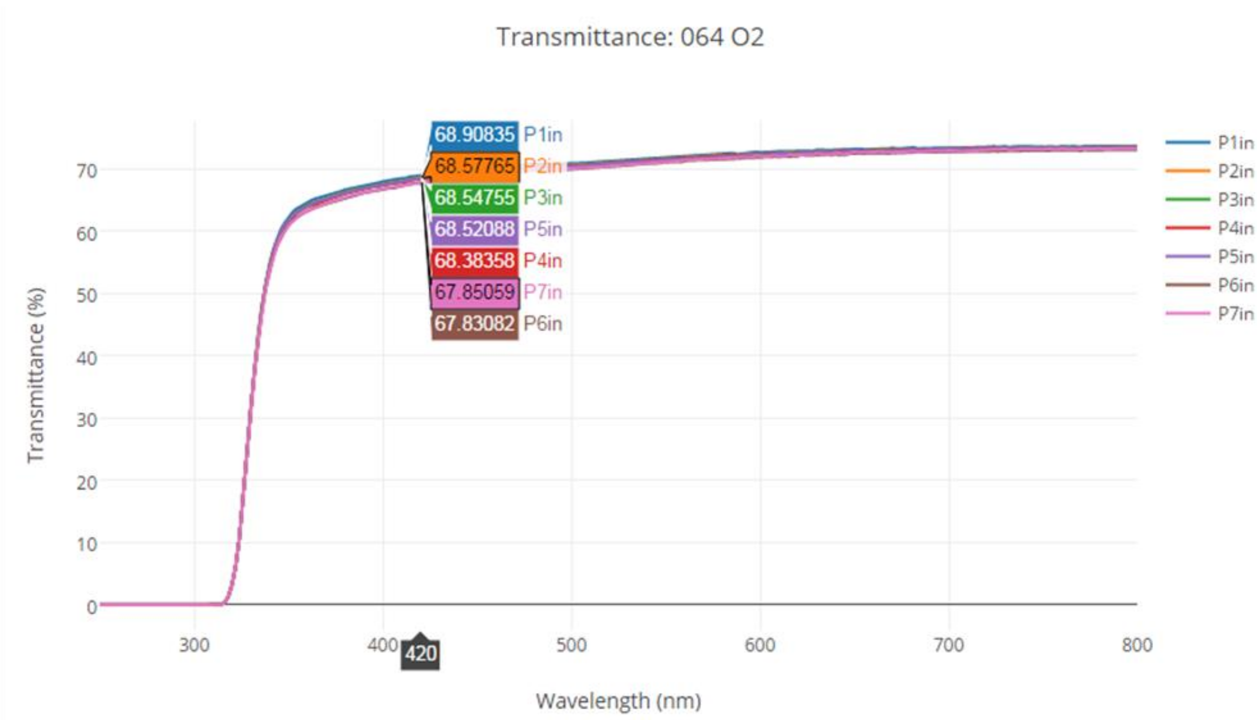


Figure 16: There is clearly a deviation between the two orientations here. Also, interestingly, there again is a trend of higher transmittance from one end of the crystal to the other.

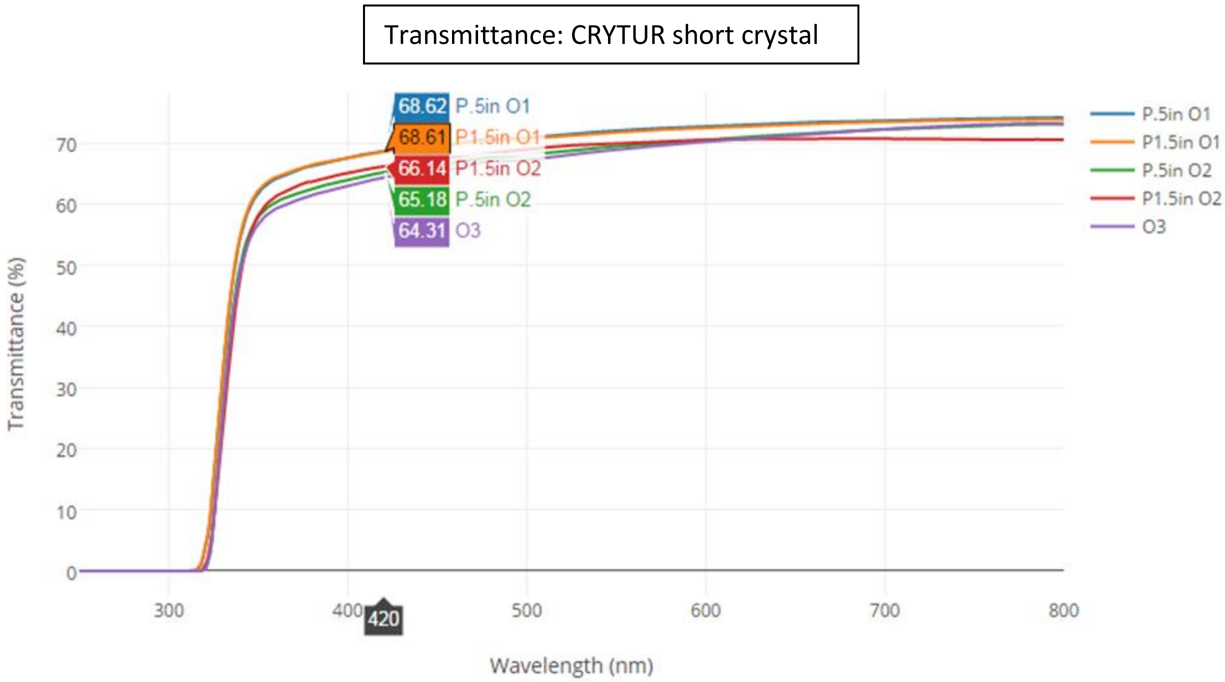


Figure 15: The shorter Czech crystal. Orientation 1 has a much higher quality than orientations two and three. This is the first crystal I have seen this to such a degree. It makes sense because they have worked with $PbWO_4$ less

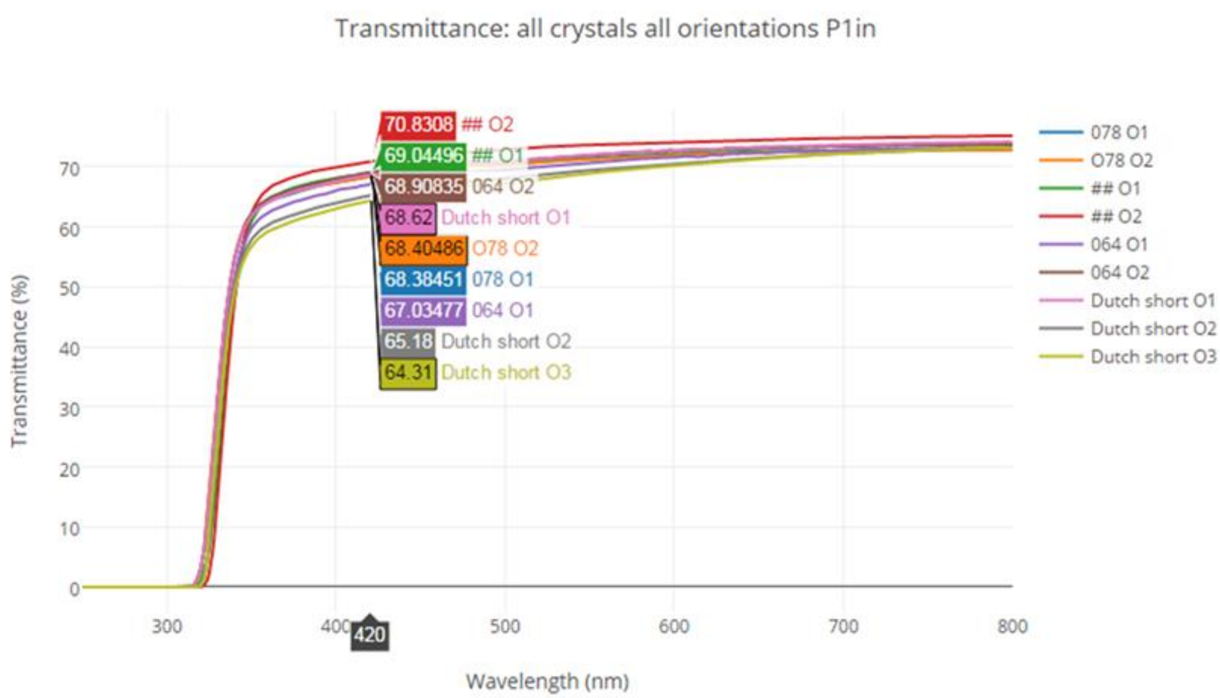


Figure 18: A graph of all of the data positioned at 1in (0.5in for the Czech crystal). The spread is about ±1.5% excluding the newer Czech crystal

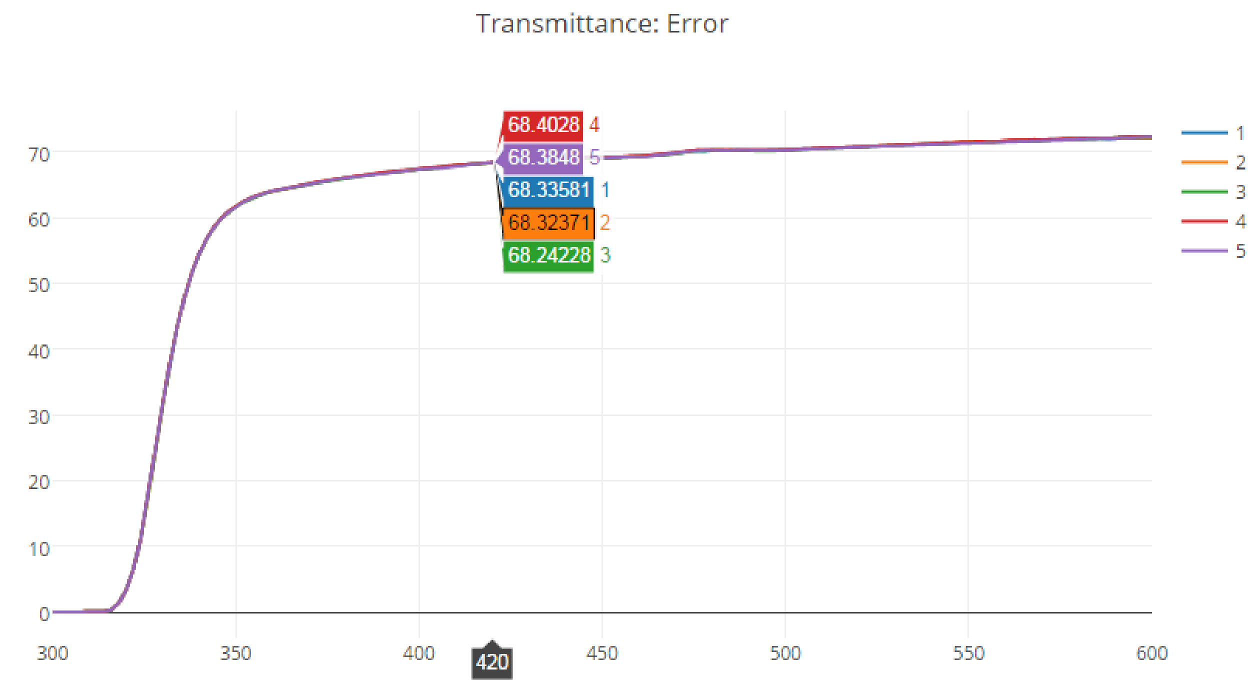
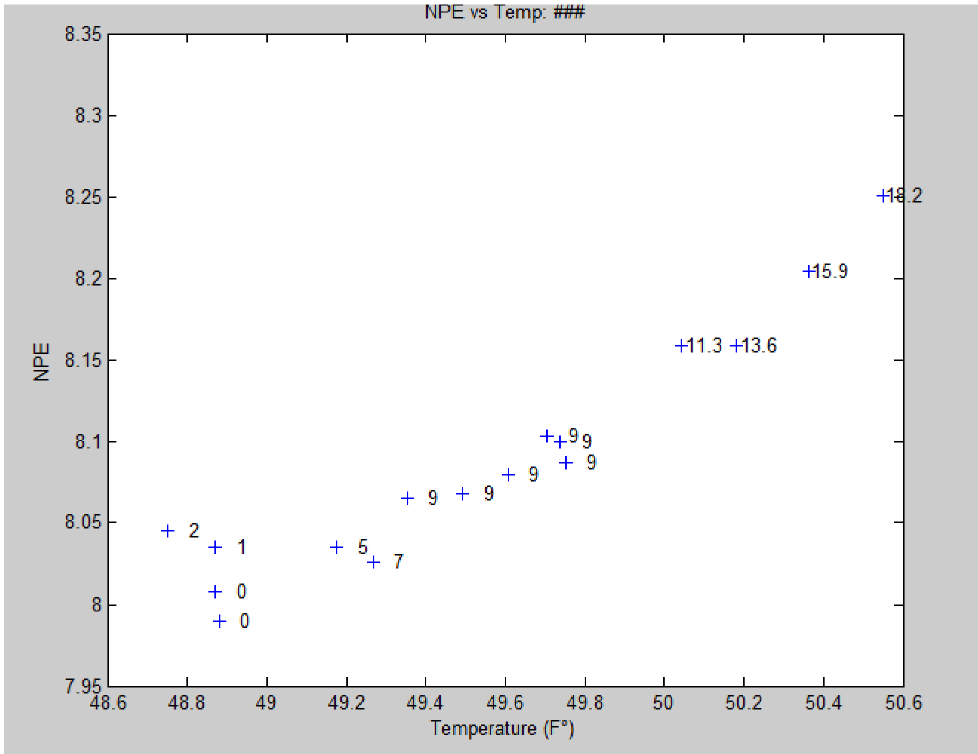


Figure 19: This shows minimum error of ±.1% with very meticulous placement. On measurements which were taken over a longer time, the error would be higher due to a higher chance of carelessness

Light Yield Results:

Based on my results, light yield clearly showed variance with temperature. Three of the crystals I measured showed a tight clustering of light yield, while one did not. I believe this was due to a bad LED connection which caused an erroneous PMT calibration. Based on the results from the three crystals, there was a clustering around 8 photoelectrons. Comparing the light yield accurately from crystal to crystal cannot accurately be done with this data due to varying temperatures. Since the energy of the radiation from the Na-22 source is .511 MeV, the light yield per MeV is roughly 15-16. This fits perfectly with the light yield of 10-15 ideal for the Neutral Particle Spectrometer. I also hoped to look for a correlation between position and light yield. Because I could not keep the temperature stable for a long enough periods of time, I was also unable to determine if there was a correlation.

Figure 20: Crystal ###'s light yield affected by temperature. The numbers next to each point represent the position (in cm)



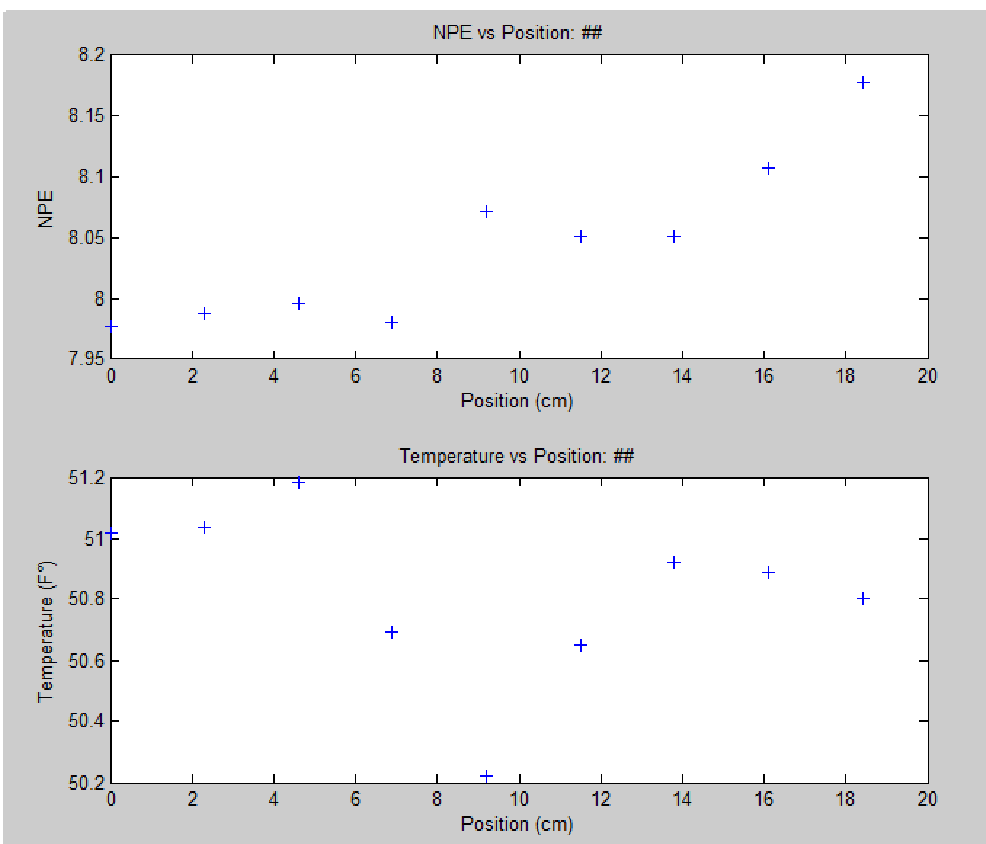
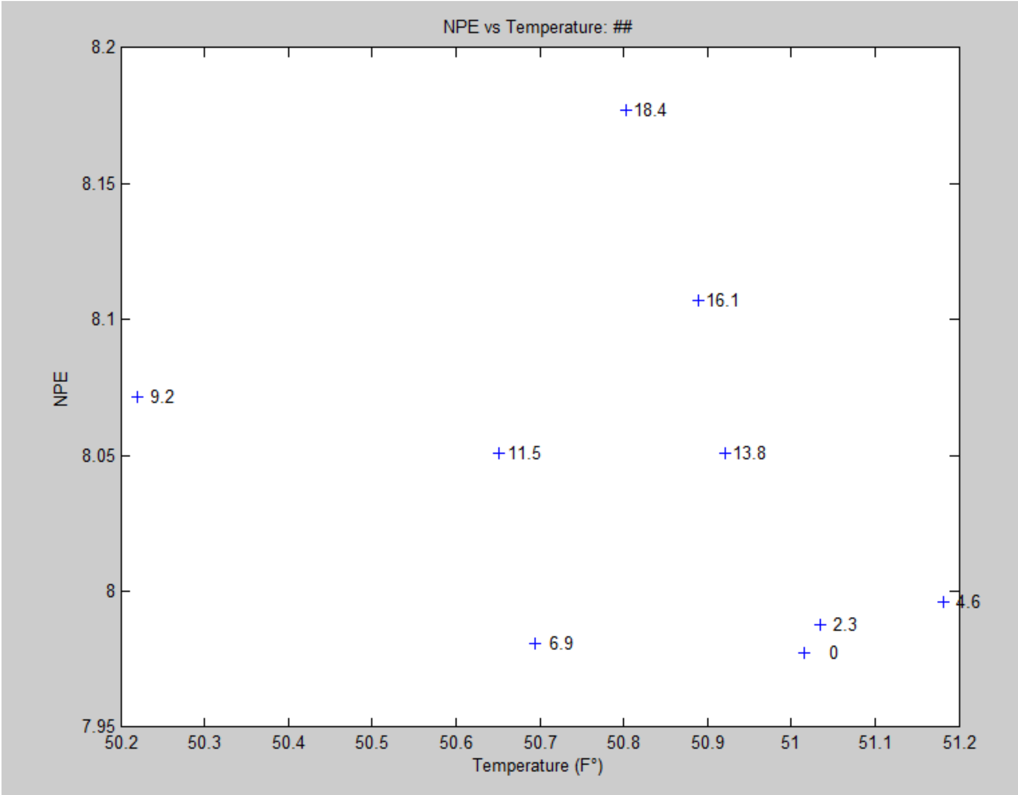


Figure 21: NPE and Temperature vs Position of crystal ###. Position was measured from 0 upward, so position~time.

Figure 22: Crystal ##'s light yield affected by temperature. The numbers next to each point represent the position (in cm). This measurement the temperature rose and fell more extremely (as can be seen in figure 9)



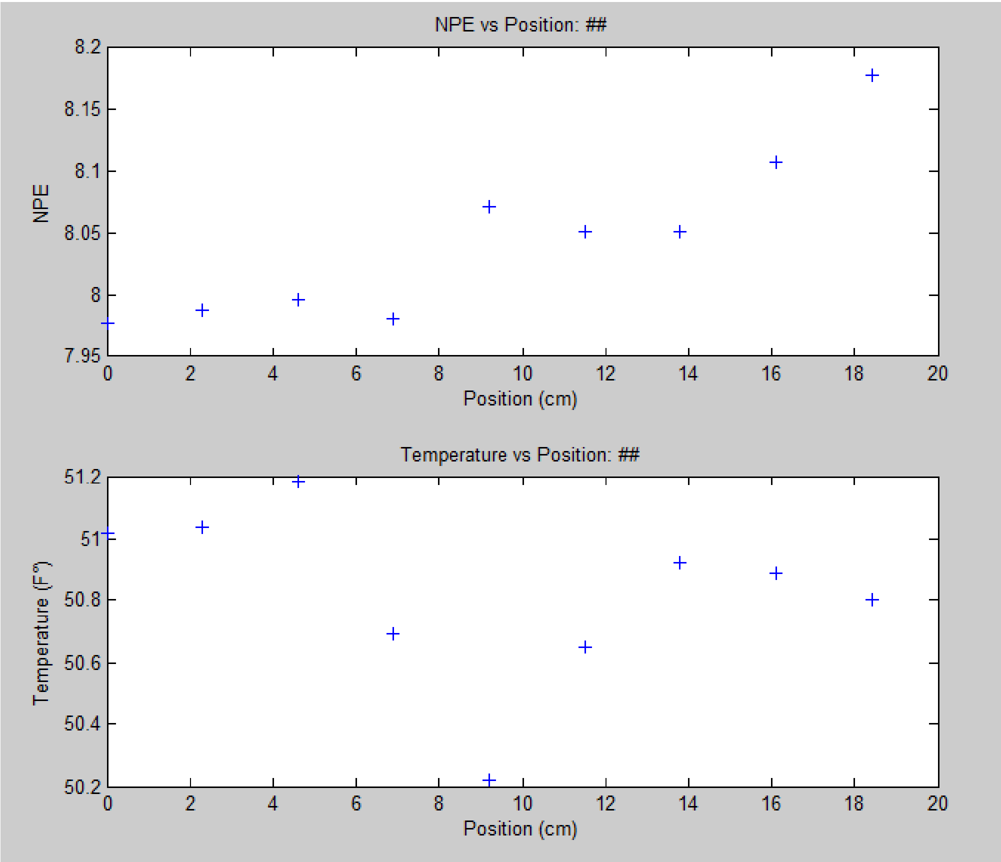
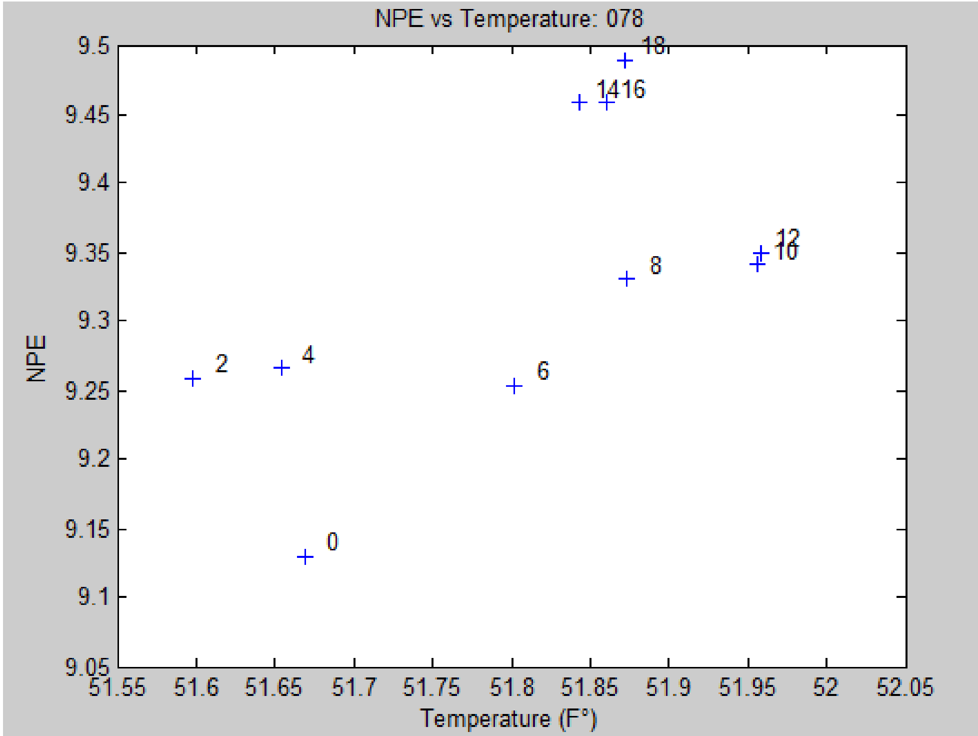


Figure 23: NPE and Temperature vs Position of crystal ##. As before and will be for the rest, position was measured from 0 upward, so position~time. In an attempt to save the temperature from rising, I unplugged the heater for a few minutes. That caused the dip from position ~7cm to ~12cm

Figure 24: Crystal 078's light yield affected by temperature. The numbers next to each point represent the position (in cm). This measurement the LED calibration went wrong. Therefore the NPE scaling is incorrect but the clustering and affects from temperature and position are still valid



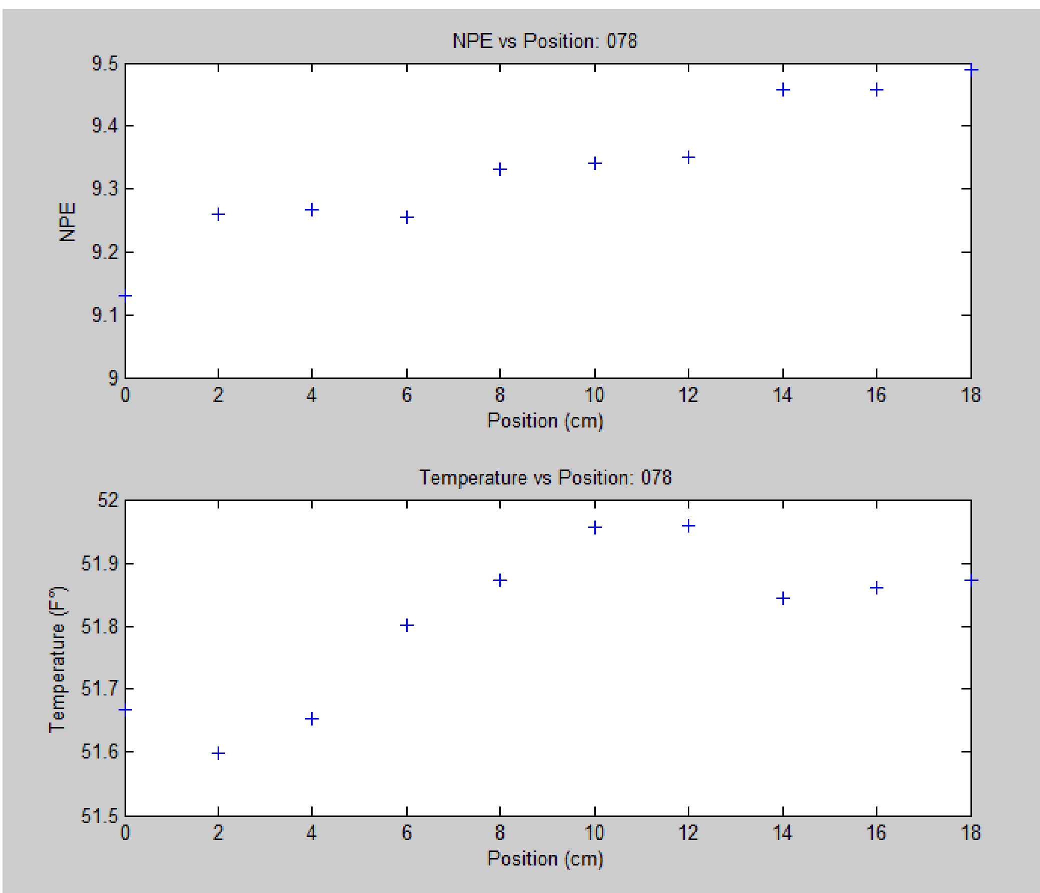


Figure 165: NPE and Temperature vs Position of crystal 078. The trend between position and temperature is visible here.

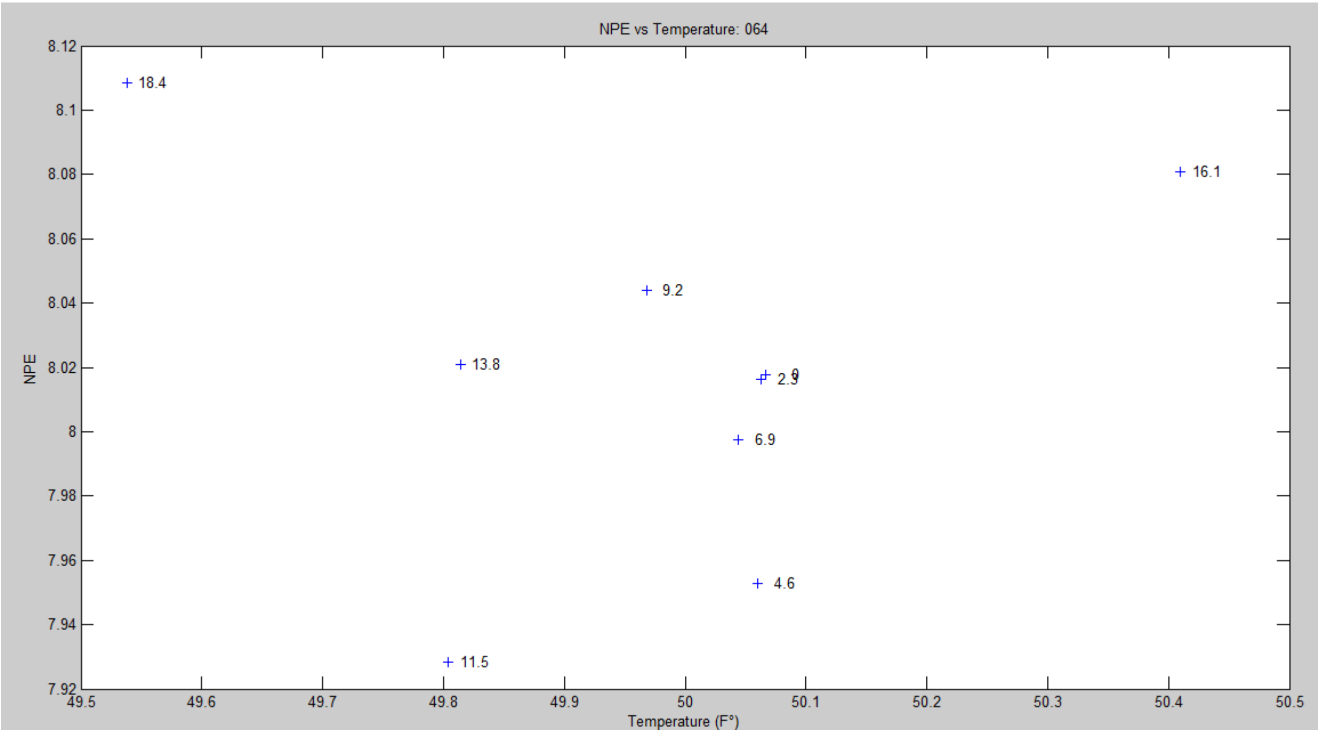


Figure 26: NPE vs Temperature of crystal 064. These measurements were the most accurate due to the least deviation in temperature.

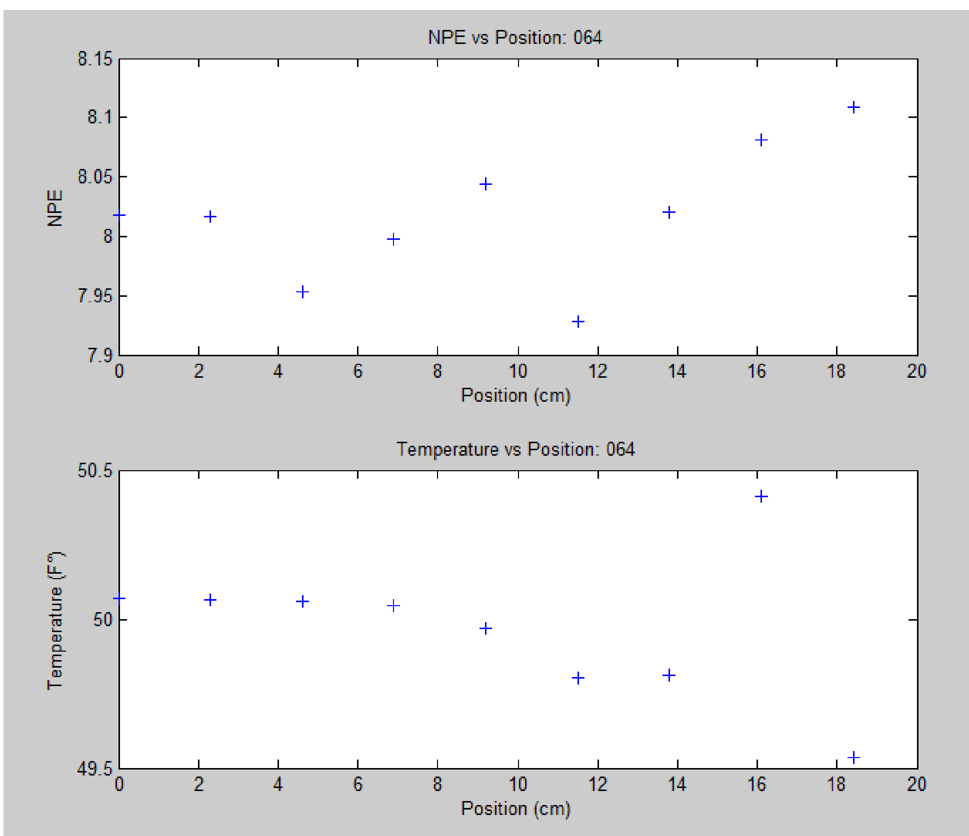


Figure 27: NPE and Temperature vs Position of crystal 078.

Discussion:

The transmittance showed that there are variations between crystals and orientations. The deviation is about ±1.5% excluding the newer crystals from the Czech company. To more accurately observe a difference along the crystal, further, more accurate data would have to be taken. I drew a perpendicular line on the styrofoam block for the transmittance to reduce error, but this still left room for human error when determining if the crystal is perpendicular. A small wooden stake (like a toothpick) could be inserted on the line so that the crystal could be placed against the stakes. However, if there is a deviation along the crystal cannot be more than ±.5%. For the refractive index, the sensitive equation proved to be the problem. It was accurate enough to confirm that the crystals, within error, are of good quality. The results also further give confidence that these crystals are PbWO4. Developing a more accurate method which could decrease uncertainty may be possible, but due to the small width (2cm) of the crystal, this may be difficult. In order to make light yield measurements, one must calibrate the PMT. Error in the light yield came from a non-consistent measurement for the calibration. Getting more consistent results of this calibration is necessary for an accurate measurement of the light yield. Further, controlling the temperature of the freezer so that it can remain within .25° F would greatly improve results so that they could be compared from crystal to crystal. Alternatively, if each crystal proved that it varied consistently with temperature, one could calculate the light yield at difference temperatures and use this data to create a function that could undo the effects of a varied temperature. The data taken proved that, even with the lowest measurements, $PbWO_4$ has a light yield which meets the parameters required for the NPS.

Sources:

[1]Taylor, Lucas. "Electromagnetic Calorimeter." CMS experiment at CERN's LHC. Available from http://cms.web.cern.ch/news/electromagnetic-calorimeter. Accessed 28 July 2015

[2] "Lead Tungstate Crystals." CMS-ECAL TDR. Available from http://cms-ecal.web.cern.ch/cms-ecal/ECAL_TDR/ref/C2.pdf. Accessed July 2015

[3] Horn, Tanja. “A PbWO4-based Neutral Particle Spectrometer in Hall C at 12 GeV JLab.” The Catholic University of America; 2015. Available from http://iopscience.iop.org/1742-6596/587/1/012048/pdf/1742-6596_587_1_012048.pdf.