GEANT4 SIMULATION OF THE COORDINATE DETECTOR

April 24, 2020

Tanner Hawk
Advisor: Dr. Edward Brash
Christopher Newport University
Applied Physics - PCSE Department

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Abstract

The goal of this project is to enhance the existing model and simulation of Jefferson Labs Coordinate Detector (CDet). The current CDet model is able to replicate 14 "paddles" of CDet out of a total 2352 paddles; the enhanced model can now replicate 196 paddles. With this increase in the size of the model, the simulation can now be used as an aid in calibrating 196 paddles as opposed to 14. The enhancement process was continued in ROOT, which was used for the development of the original model, and the data analysis is done using C. The data resulting from the simulation was fit with a Gaussian fit on the pedestal and the data distribution. The fit on the pedestal was used to obtain a relative zero value and the fit on the data was used to obtain a mean number of emitted photons. The relative zero value is then subtracted from the number of emitted photons and compared to the value of the Analog to Digital Converter that is obtained from real-life data. A proportionality constant is then calculated which is the ratio of the Pedestal-Subtracted number of photons to the average energy deposited by a vertically tract muon in the physical Coordinate Detector. This comparison value is then used to assist in the calibration of the physical detector.

Contents

Introduction

Jefferson Lab's Coordinate Detector (CDet) will be used in the upcoming Neutron Polarization run in Jefferson Labs Hall A for charged particle negation. As a particle passes through the detector, energy will be deposited in the detector proportional to the momentum and charge of the particle. Knowing the expected amount of energy to be deposited into the detector by a specific particle will allow for the automatic negation of data resulting from particles that are not of interest. The overall goal of the Neutron Polarization Run is to determine the inner structure of the neutron. It is well known that a neutron is comprised of three quarks: two down and one up. This experiment will allow for a further understanding of the structural layout of these three quarks. Information regarding the distance that the quarks are from one another and the expected radius that each quark has from the center of mass of the neutron are just two of many potential unknowns that could be answered with this experiment.

Coordinate Detector

The primary detection component of the CDet is comprised of scintillator paddles. As a charged particle passes through the scintillating plastic of the paddles, the molecules that the charged particle passes by will ionize and then reabsorb electrons which will then produce photons. These photons then move into a wavelength shifting fiber (WLS fiber) that shifts the photons wavelengths from blue to green. The WLS fiber is attached to a coupler and the coupler is attached to a multi-anode Photomultiplier Tube (maPMT). A Photomultiplier Tube (PMT) takes in a photon and amplifies it via a dynode chain which produces an electron cascade. The total charge resulting from the cascade is proportional to the voltage difference among different metal plates, the respective work functions of the plates, and the energy of the initial electrons. The initial electron count will be proportional to the energy deposited in the paddle by a particle. A maPMT contains 16 amplification systems laid out in a 4 x 4 matrix. Each individual amplification system is referred to as a "pixel" and each "pixel" produces a signal in the same manor of the normal PMTs mentioned above.

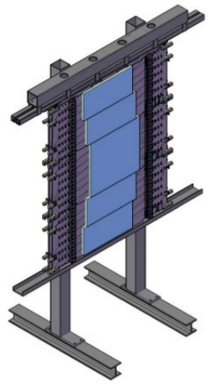

Figure 1: Jefferson Lab's Coordinate Detector

Each "bar" of CDet is comprised of 14 paddles, and therefore, only 14 pixels of each maPMT will be used. The final charge signal output by each "pixel" of a maPMT is then passed to an analog to digital converter (ADC) which turns an analog signal into a digital square pulse dependent on the analog signals value. The ADC takes in the analog pulse and records the total charge of the pulse. Then, via a fixed precision, it relates that total charge to a square pulse of a proportional size. This ADC signal should be proportional to the energy deposited into a scintillator paddle by a charged particle. This detector will be used for particle identification and to track the trajectory of the particle. Energy deposition is an important piece used in particle identification and the use of many different paddles allows for the trajectory of particles to be understood.

Furthermore, each of the PMTs of CDet are made and attached to the WLS fiber in each paddle by hand. The human involvement in the making of the detector provides deviations in the output of each PMT. Since each paddle and PMT has its own efficiency, any model must be able to provide an expected value for each of the paddles instead of comparing all real-life paddles to the same simulated paddle or bar. The physical placement of the bars in the detector also provides variances in the output of each PMT as some of the energy in each paddle can spill over into the neighboring paddles.

Goal of Project

The goal of this project was to enhance the existing CDet model to more accurately represent the real life detector. Doing so allows for the simulations to produce more accurate results that will better allow for the calibration of the maPMT's to output signals of appropriate values. The desired calibration is the ratio of simulated output photons to the energy deposited in the detector by a celestial muon. The existing simulation only modeled one bar of the detector and the analysis programs could only handle single bar analysis. This was problematic as the entire detector is comprised of 168 bars: 14 paddles in a bar, 14 bars in a half-module, three half-modules in a side, two sides in a plane, and two planes in the detector. The model has been updated to be expandable to the entire size of CDet however, for the data comparison that was done, only a half-module, or 14 bars, of the detector was modeled. Not only was the size of the model of CDet increased, the trigger setup was increased to match the real-life setup: four trigger paddles, two above and two below the detector. Additionally, the analysis manager and analysis programs are able to analyse the entire detector as a single unit, or analyse a single bar at a time; single bar analysis allows for more precise comparisons to real-life data. Obtaining a more accurate comparison between the enhanced model and the real-life muon data allows for the simulation to be used calibrate the physical CDet for use with incident electrons in the experimental hall.

Theory

The backbone of this project is the real-life data runs which trigger on vertically tract muons as the comparison tool for the simulation which also utilized muons and the same trigger set-up. Comparing these two sets of data allows for a proportionality of the output values to be obtained. While the real-life data set outputs values in units of ADC bins, the simulation outputs the number of photons emitted by each paddle. While ADC bins can be seen as very vague, upon further examination, these values can be directly translated to energy deposition in the paddle to which the PMT that is being read is connected. Determining a relation between a simulated number of photons and physical energy deposition is key and that is the goal of this project. As said above, the muon comparisons is the backbone of this project. Upon these first comparisons further, more valuable, comparisons can be made. By changing the simulation to run with incident electrons, instead of muons, the user can then obtain the number of photons emitted by each paddle and utilize the relation determined by the muon comparisons to determine the expected ADC value of the real-life detector when hit with electrons.

On the simplest of levels, both the simulation and real-life detector provide a value of energy deposited in each of the detectors paddles. The simulation provides this information with a number of photons emitted at specific energies, and the physical detector accomplishes this with the ADC output. Comparing the two allows for a further understanding of what is going on inside the physical detector. Knowing that a certain number of photons is equivalent to a certain number of ADC bins aids in further understanding how particles are interacting inside the detector.

Detector Model Enhancement

The bare-bones design choices have already been chosen for me. The existing model utilized two C tool-kits, ROOT and Geant4. The only design choices that were made were linked to the enhancements that added to the existing model: a more real-to-life trigger setup and an increase in the number of bars in the model and the implementation of incident electrons. Furthermore, the provided code modeled a single bar of CDet and a single trigger, or four, of the trigger set-up. The existing model of CDet is shown in Figure 2 below. The bar is roughly 50 centimeters long and each of the 14 paddles is roughly 0.6 centimeters thick and four centimeters tall. The single trigger paddle is placed one centimeter above the bar.

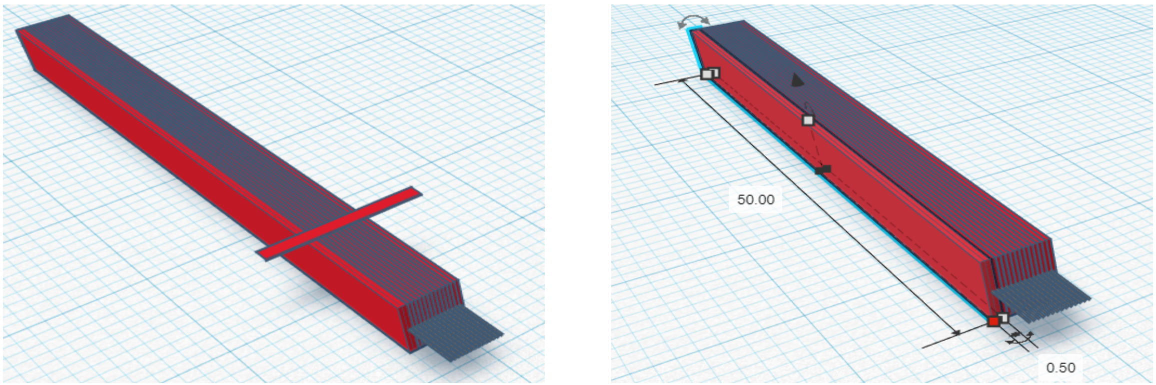

Figure 2: Model of CDet Created by Existing Code

Detector Size

The first enhancement that was made to the existing model provided the ability to increase the size of the detector from the 14 paddles to the current 196 paddles. This will allow for a better understanding of the signals from the paddles on the edge of the first bar, as the 14th paddle of the older model output unexpected signal data. It will also allow for the analysis of energy spread and distribution over more bars. Initially, two different plans were created as to how to implement this in the existing model. First, there was an attempt to create a paddle object. This object would be passed a position vector and an

ID number and it could be called for as many paddles as needed to be created —in this case, 196 times. However, after implementing this method, many errors began appearing in the simulation. To fix the resulting errors, many more objects had to be passed into the paddle method: a glass G4material, a plastic G4material, the inner WLS fibers, and the fiber cladding to name a few. As the Detector construction file began to change, the behind the scenes actions of Geant4 started to cause a lot of issues; pointers were not being deleted, pointers were being created more than once, information was not being passed from the object creation methods to the main method. All of these issues resulted in this idea being scrapped.

Starting over, the plan was to increase the iteration amount in the areas in which the paddle, PMT, cladding, fibers, mirrors, and mylar sheets (these surround the paddles) were created. In order to accomplish this, nested loops were utilized, one loop for each section of the detector: paddles, bars, modules, sides, and planes. In the most inner loop, a method is called to return an ID number for the corresponding paddle. The user can define how many paddles are to be created by setting a desired number to be created for each of these sections. For example, in order to create the 196 paddle, half-module, detector, the user sets the number of paddles and bars to be 14 and the number of modules, sides, and planes to be one. Once this was implemented properly, the model of the detector was successfully expanded to model that shown in Figure 3 below.

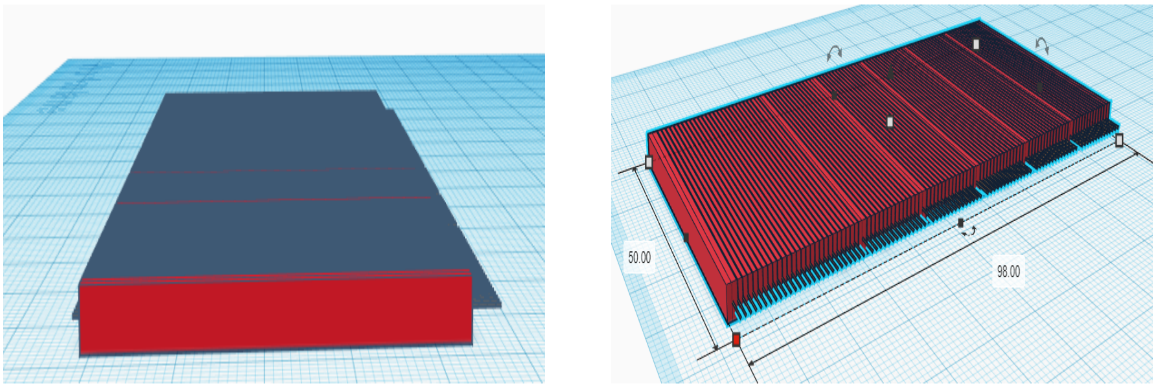

Figure 3: Model of CDet Created by Enhanced Code

The half-module extends roughly 196 centimeters in width and is still four centimeters tall and 50 centimeters long. The same length and height of one bar, and 14 times the width of a single bar which is as to be expected.

Trigger Setup

The implementation of the real-life trigger setup will create more life-like data from the simulation which will result in a more accurate comparison to the test data. Similarly to how the increase in detector size was initially planned, there was also two plans for increasing the number of trigger paddles: Increase the width of the paddle or turning the current trigger paddle creation code into a method. Initially, streamlining the creation of the model via "trigger objects" seemed to be a simple task. However, while expanding the number of paddles in the detector, the plan to create a similar trigger method was nixed. The real-life trigger setup in the model was created through a loop of number of desired triggers. In this loop there is a similar method for obtaining a trigger paddle ID number and the placement vector for each paddle is defined outside of the loop. The resulting trigger placements are shown below in Figure 4.

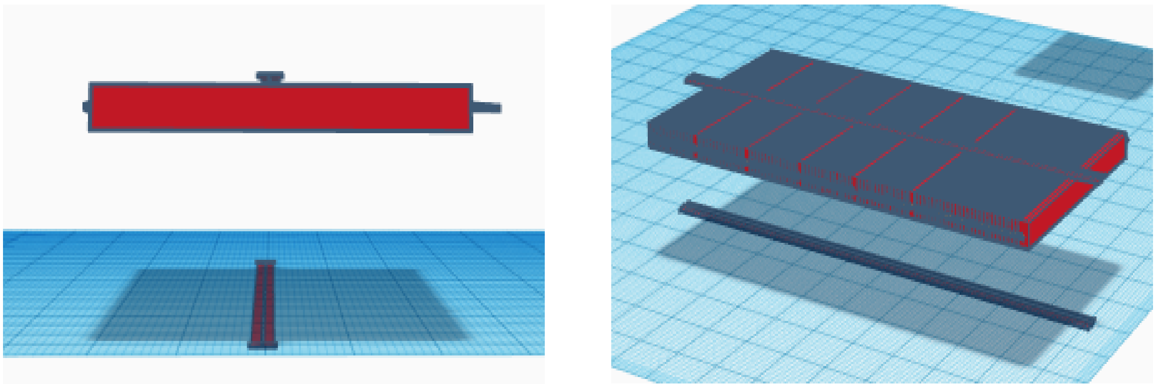

Figure 4: Model of CDet Created by Enhanced Code

There is a gap of one centimeter between the half-module and the two trigger paddles above the half-module, just as in the initial model. The additional two trigger paddles are 20 centimeters below the half-module. The addition of these three trigger paddles and their placements correspond to the placement of the four trigger paddles in the set-up that was used to obtain the real-life data that will be used for comparison.

Primary Particles

The original model created muons one centimeter above the trigger paddle in a sheet that covered the single bar. The height of the primary muon plane was not changed, but the area of particles was increased to cover the entire half-module. Once the are of the particle generation was increased, the number of primaries being generated needed to be increased 14-fold. This increase in particle number was necessary to keep the primary particle density the same as the original model. Figure 5 below shows the area in which the primary particles are generated.

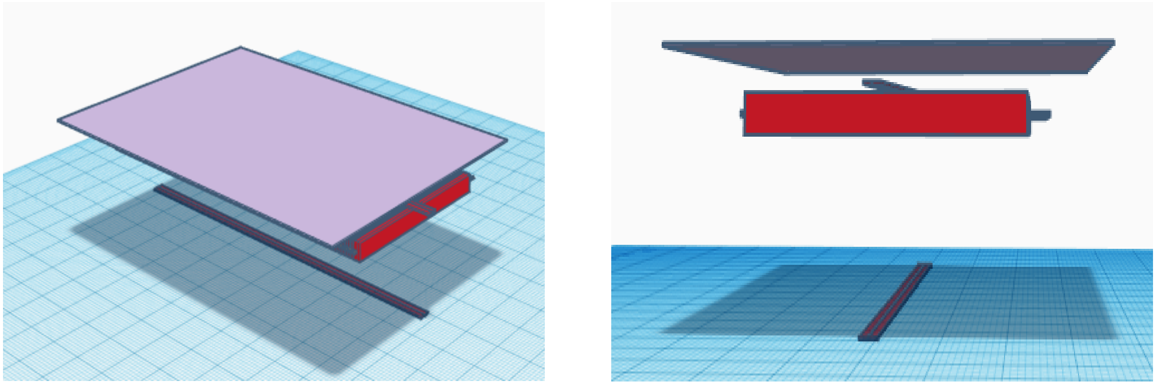

Figure 5: Plane in which Primary Muons Begin

The ability to change the primary particles from muons to electrons was also implemented in the simulation. This allows for the simulation to be used to calibrate the physical detector. This change was made by allowing the user to vary the primary particle ID number to that of an electron, as defined by Geant4. The primary particle generator function then creates electrons with the energy distribution akin to that of the electrons exiting the electron beam at Jefferson Labs. Likewise, the primary particle momentum distributions were also changed to be entering CDet perpendicular to the paddles, instead of entering at an angle like with the primary muons. With the addition of this feature added and tested, the primary particle creation was then set back to muons so that the calibration of the simulation could be continued.

Data

Data analysis and comparison is essential to determine if the model is to scale and the simulation has run properly. The simulation outputs Root data files which organize the data. The quickest check to see if the simulation has run properly is to look at the histograms in these files. These histograms allow the user to ensure that the primary particles, detector components, and trigger components were created and placed correctly. Once the model was ensured to be correct, data analysis could take place. One of the primary analysis programs used was “AnalyseSignals”, a C file that was built around the initial model and needed to be altered for use with this larger model. To accommodate the increase in size of the detector model, single bar and half-module analysis were implemented. The methods in this file provide histograms which allow for an additional check of the models size and positions which depend on the trigger set-up working correctly the organization of components in the detector construction files. After ensuring the detector was modeled correctly and the simulation runs as expected, data comparison can be done. The desired comparison is the proportionality constants of each of the paddles of the first and seventh bar of the first half-module of the Coordinate Detector.

Raw Data from Simulation

Upon running the simulation, viewing the data stored in the Root file that the simulation outputs, provides insight on the effectiveness of the simulation. For example, you can look at the distribution of detector positions, as shown in Figures 6, 7, and 8 below. These distributions provide quick feedback to determine if the detector is the appropriate size, is placed at the correct vertices, and that components are not overlapping.

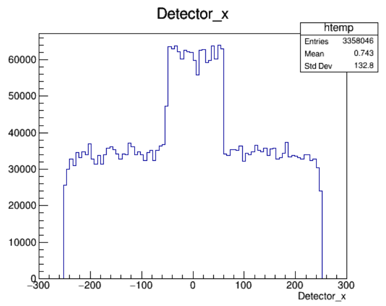

Figure 6: X-axis distribution of CDet half-module

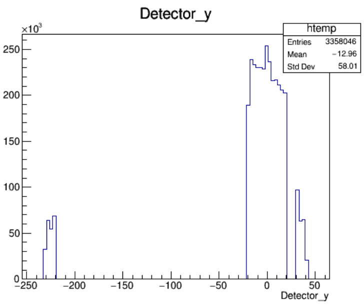

Figure 7: Y-axis distribution of CDet half-module

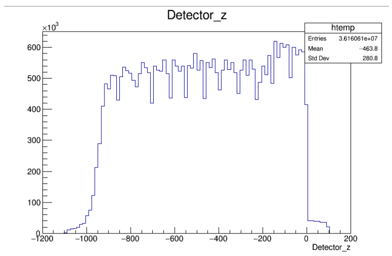

Figure 8: Z-axis distribution of CDet half-module

In Figure 6 you can see that the model of CDet in the simulation extends from negative 25 centimeters to positive 25 centimeters, totalling to the detectors physical length of 50 centimeters; the additional hits in the center of the distribution show the position of the top and bottom sets of trigger fingers. Likewise, the histogram in Figure 7 provides verification that the distance between the upper trigger fingers, the distribution furthest right, and CDet, the middle distribution, is exactly one centimeter. This same histogram also shows the gap of 22 centimeters between CDet and the bottom trigger paddles, the distribution furthest left. Not only does the data shown in the TTree give insight into the position of the detectors, it also provides energy depositions, primary particle information, and timing distributions which show the time that particles pass through the different detector components. However, this information is more useful once passed through analysis programs.

Analysed Data using Enhanced Analysis Program

One of the primary analysis programs that I used provided several groups of histogram plots. These groups included trigger and paddle positions, primary particle energies and momentum distributions, detector number of hits, energy deposition, and the number of photons emitted from each paddle. However, after the model of the detector was expanded past 14 paddles, the analysis program stopped working. Once the program had been fixed and allowed for the analysis of all 2352 paddles in CDet, far too many plots were being created. To account for this, single bar analysis was added into the program so that each plot method could be passed an integer correlating to which specific bar the user is looking to analyze. The fifth plotting method highlights this function perfectly.

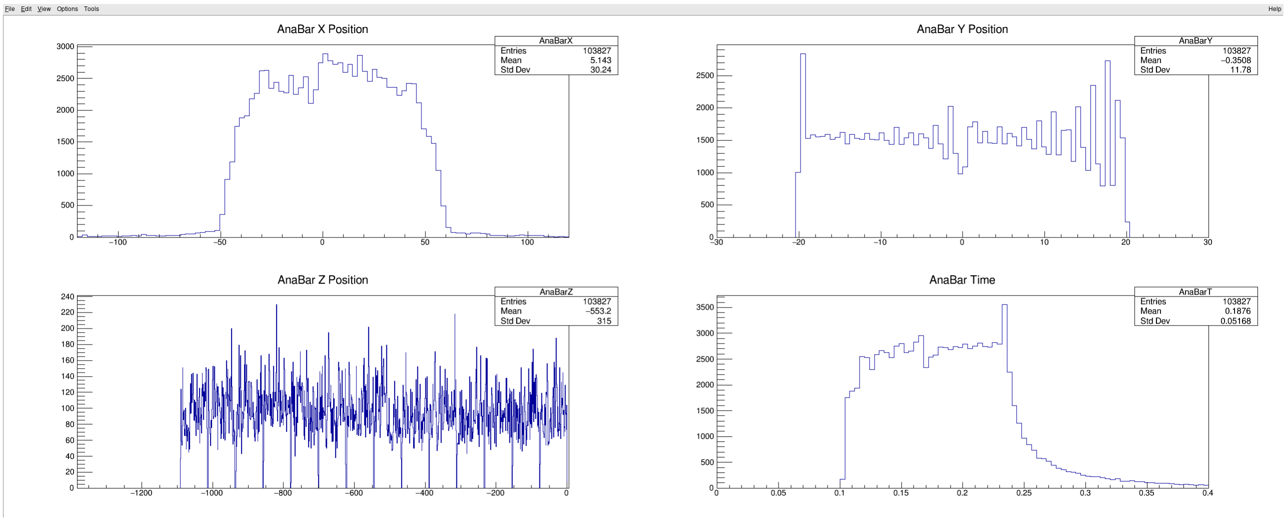

Figure 9: Cartesian positioning of entire half-module and timing of primary hits

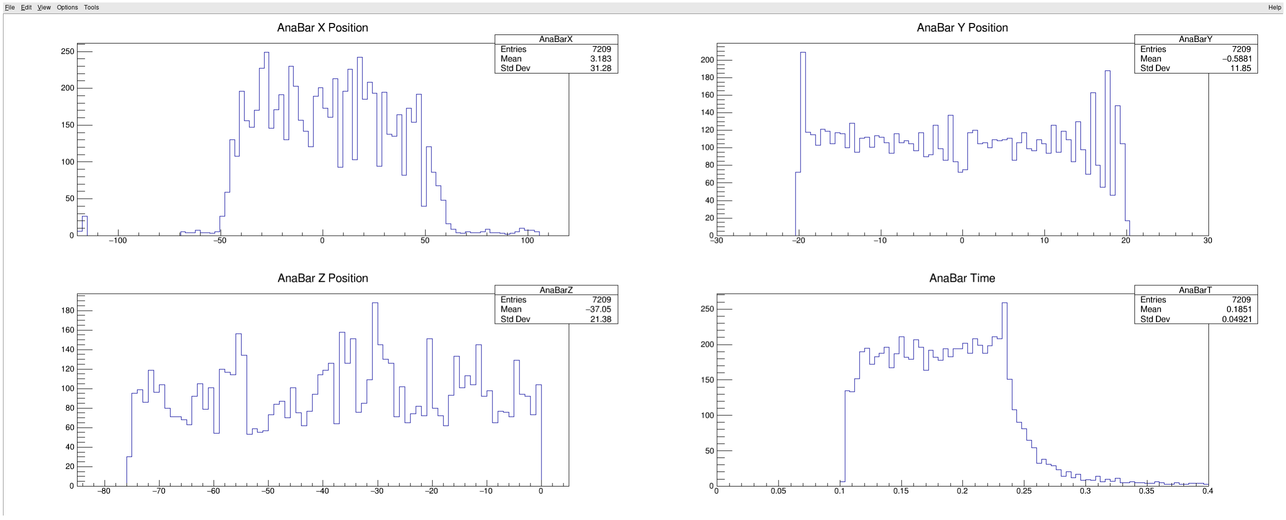

Figure 10: Cartesian positioning of First Bar of half-module and timing of primary hits

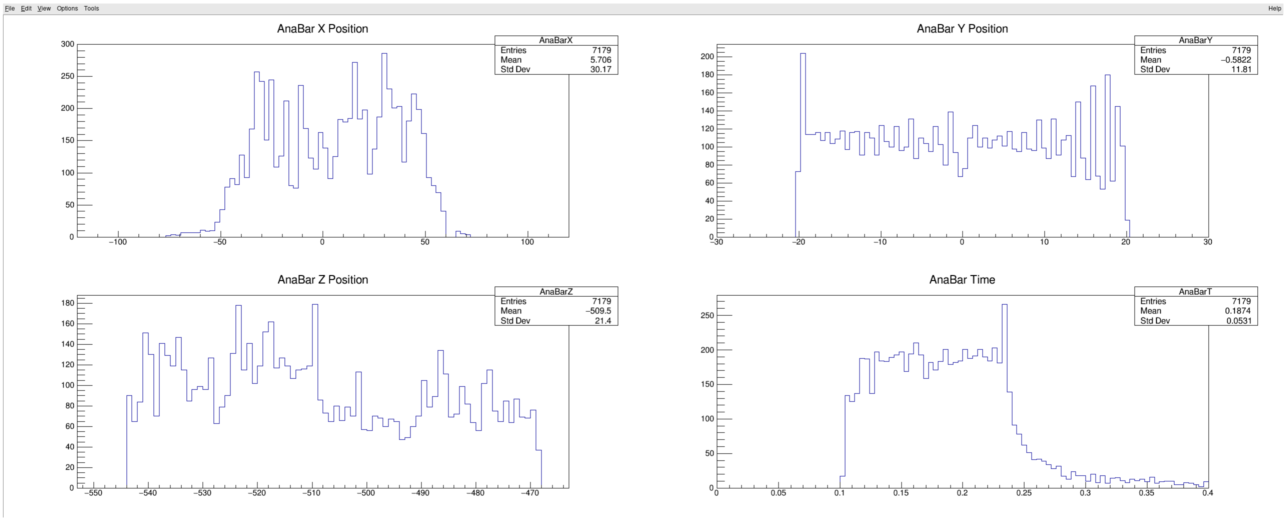

Figure 11: Cartesian positioning of seventh bar of half-module and timing of primary hits

The primary histogram of focus in Figures 9, 10, and 11 is the one in the bottom left of each figure, "AnaBar Z Position." In Figure 9, any particle that passes through the half-module is being counted which can be determined by further examining the 14 different sections to the 'AnaBar Z Position' histogram, where each section is one of the 14 different bars in the half-module. Only particles that pass through the first bar are being counted and shown in Figure 10, which can be validated by the range of the 'AnaBar Z Position' histogram. Likewise, only the particles passing through the seventh bar of the half-module are being counted for Figure 11. This specific graphing method is very useful in ensuring that the user has modeled the detector in the simulation to the correct size and placed at the positions that are desired.

Proportionality Constants

The primary reason for this enhancement of the model and simulation of CDet, is to allow for a more accurate proportionality constant. While the initial model compared the first bar of CDet in the simulation to the real-life data obtained form the seventh bar, the current model allows for each simulated bar to be compared to the corresponding real-life bar. In order to get a comparison between the enhanced model and the existing model, proportionality constants were calculated via comparison of the first bar of the simulation to the seventh bar of the real-life data.

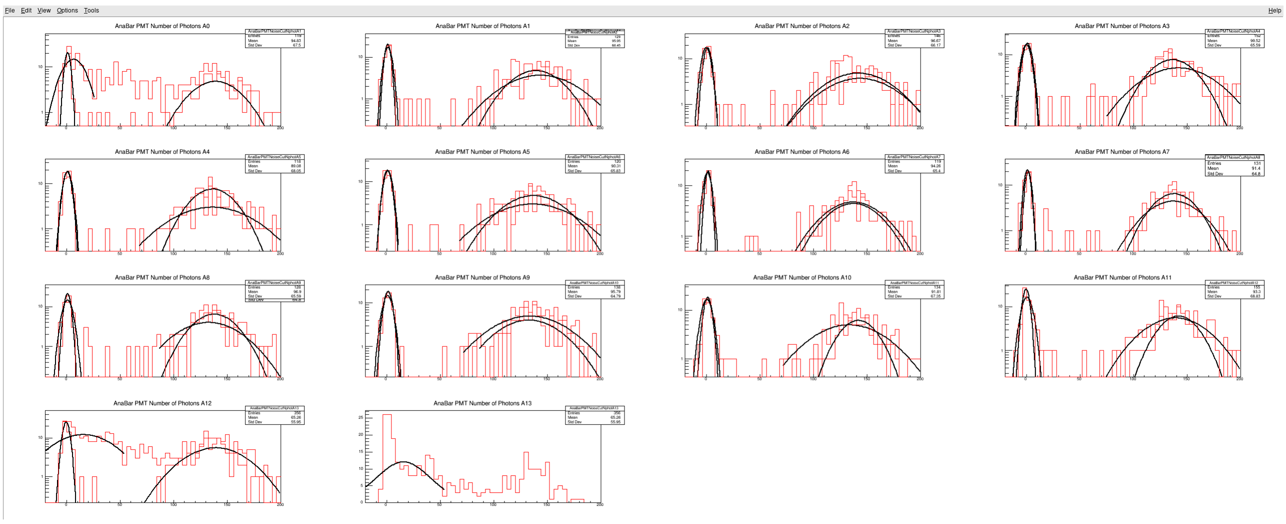

Figure 12: Number of photons emitted by each simulated paddle in first bar

Figure 12 above shows the number of photons emitted from each paddle of the first bar of the simulated half-module. The Gaussian fit applied to the left side of each histogram is used to obtain the pedestal value. The Gaussian fit applied to the right side of each histogram is used to obtain a mean number of photons. The pedestal value was then subtracted from each of the mean photon values and the resulting number is recorded in Table 1 below. The same proportionality constant calculation was done with the existing model (comparing bar one of model to bar seven of real-life data). The average number of photons per paddle of the first bar in the existing model and enhanced model is shown in Table 2 below. Additionally, Table 2 includes the proportionality constants given by the comparison between the first bar of the existing/enhanced model and the real-life data of the seventh bar. The proportionality constant shown in Table 2 is calculated by dividing the number of photons by the 7.24 MeV. This value was used because it is within the range of energy deposited by a celestial muon in the actual detector.

Table 1: Pedestal Subtracted Photon Count

Paddle 0	128.17 photons
Paddle 1	143.04 photons
Paddle 2	139.11 photons
Paddle 3	136.71 photons
Paddle 4	133.84 photons
Paddle 5	131.08 photons
Paddle 6	138.44 photons
Paddle 7	136.01 photons
Paddle 8	136.12 photons
Paddle 9	141.17 photons
Paddle 10	141.36 photons
Paddle 11	142.67 photons
Paddle 12	143.67 photons
Paddle 13	140.05 photons

Table 2: Existing versus Enhanced Model

	Existing Model	Enhanced Model	Percent Difference
Photons/Paddle (1^{st} Bar)	117	138	16.47%
Proportionality (1^{st} Bar)	16.2 Photons/MeV	19.06 Photons/MeV	16.22%

Discussion

The expansion of the detector from a single bar to a half-module was done to aid in the obtaining of a more accurate proportionality constant for the eventual calibration of CDet for incident electrons in the experimental hall at Jefferson Labs. It was expected that this increase in size would not vary the proportionality constant previously obtained with the single bar model. If any variance was to be expected, an increase in the number of photons emitted from each paddle of the model would be understandable. As the number of paddles increased, the area of which energy deposition from muons would increase. The energy deposited in a paddle can spill slightly over into a neighboring paddle or PMT and thus more electrons could be emitted. This idea could be backed up by the data shown in Table 2 above. However, it is also important to note that the increase in the number of photons emitted could be related to a change in the number of primary muons being generated over the each paddle of the detector. While a 16.47% difference between the existing and enhanced models emitted number of photons could be interpreted as a large gulf, the user needs only to know the current models proportionality in order to calibrate the real-life detector for electron runs. If the user would like to bring the number of photons, and thus the proportionality constant, closer to the value obtained from the existing model, or any other number, then a change in the density of primary muons would accomplish this goal.

Furthermore, upon the inception of this project, the goal was to obtain a comparison of the seventh bar of the model against the seventh bar of the real-life detector. The existing model compared the first and only bar of the model against the seventh bar of the real-life detector. The same comparison was done with the new model and is shown in Table 2. The data analysis programs are in place to allow this desired comparison with the ability to fit each bar of the model to obtain the number of photons emitted from each paddle of the specified bar. However, with the increased amount of primary particles required to cover the entire detector, the time to run the simulation increased 14-fold. Unfortunately, at this time there is no data with trigger hits and particles passing through the seventh bar and there is no more time this semester to run another simulation and run the analysis program to obtain the emitted number of photons from each paddle of the seventh bar. This is a simple task that could be done in a future enhancement of the model and simulation.

Overall, the model was expanded from a single bar to a half-module of CDet; three additional trigger paddles were added to match the real-life trigger system. The two main analysis programs were modified to allow for single bar analysis and an overall half-module analysis for methods that could make use of this. Each of these methods that required a trigger to occur were also modified to trigger when a primary particle passed though both the top and bottom sets of trigger paddles instead of a data cut being placed on primaries with entry angles that would result in a particle not padding completely through a bar of CDet. While proportionality constants were not obtained for a comparison of the seventh bar of the model to the seventh bar of the real-life detector, this ability is in place and simply requires a functioning run of the simulation with a desired primary particle area and density. With appropriate real-life data, a comparison of each individual bar of the model to its corresponding bar in CDet could also be obtained.