Background Simulations with a Transversely Polarized Target

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Abstract

I ran simulations under the supervision of Dr. Latifa Elouadrhiri and Dr. Andrey Kim to study the electromagnetic background of the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS12) detector. The goal of the experiment was to identify what effect a transverse magnetic field that continuously polarizes the target. In this case ammonia (NH_3). The transverse field causes particles to bend. This creates more noise in data and reduces the life cycle of the Drift Chambers (DC).

In the beginning stages of the experiments, I reproduced the results from Run Group A (RGA) Fall 2018. I used this stage to familiarize my self with GEANT^4 Monte Carlo software. The next stage was testing the transverse field by removing any equipment in the CLAS12 that would interfere with the data. The final stage of the experiment was to test two different configurations of the CLAS12 detector. The first configuration was the target located at $(0, 0, 0)\,cm$. The second configuration was the target shifted $(0, 0, -75)\,cm$ away from the CLAS12 detector.

The results from both configurations show that when the target shifted $-75cm$ away from the CLAS12 detector it actually increased the occupancy in DC. When confronted with this data, RGH has decided to focus their attention on the first configuration. There will be further simulations conducted with all of the equipment added back into the CLAS12.

1. Introduction

The Jefferson Lab Hall-B physics program was looking to introduce a transverse polarized target. This is assigned to Run Group H (RGH). The transverse target has three sets of measurements:

- Deeply Virtual Compton Scattering.
- Inclusive hadron production in Semi-Inclusive Deep Inelastic Scattering (SIDIS).
- Di-hadron production in SIDIS.

The requirement to test these measurements is a transversely polarized target within the CLAS12 detector. HDIce was the primary option. However, at this time RGH is not ready to implement HDIce because it is still in the research and developement stage. There are three options that were examined as an alternative to HDIce:

(1) A frozen-spin target of NH_3 inside the CLAS12 solenoid and operating at $0.2K$ and $2T$.(I did not participate in this part)
(2) A target of NH_3 that is continuously polarized at $0.3K$ and $2.5T$ inside the CLAS12 solenoid.
(3) A target of NH_3 that is continuously polarized at $1K$ and $5T$ in place of the CLAS12 solenoid. The target is disconnected and moved away from the detector.

All three of these options use Dynamic Nuclear polarization (DNP) to polarize free protons in a target such as NH_3. DNP targets polarize higher and faster. They have a better resistance to beam heating and radiation damage. However, they produce a higher percentage of unwanted background nuclei in the target. They also have a reliance on high-strength, high-uniformity magnets for the polarization process. This raises concern for the cLAS12 transverse experiments. This creates an interference with the longitudinal field of the CLAS12 solenoid which increases the electromagnetic background from the interaction of the transverse field and scattered electrons.

Option 1 uses a frozen-spin target; the target is polarized using a separate field magnet. In this case, a 2.5 or $5T$ high-uniformity superconductor magnet. The target is cooled to $0.2K$ and a transverse field is surrounded by a Type II bulk superconductor MgB_2 to shield the CLAS12 solenoid's field and provide a transverse field for DNP.

Option 2 has many similarities to option 1. It uses the Type II bulk superconductor MgB_2 but a more uniform transverse field is trapped inside. This option poses the greatest threat to the target because it requires a highly uniform ($100ppm$), persistent field to be generated by the MgB_2 shield.

Jefferson lab has used dynamically polarized targets, options 3, for multiple occasions at luminosities that exceed $10^{36}cm^{-2}s{-}1$. Since, RGH is running the simulations at a much lower luminosity, the performance could be reliably predicted. The issue with this option is that it is incompatible with the CLAS12 detector.

It does provide the highest average sample polarizations and can operate at luminosities more than an order of magnitude greater than the limits of the CLAS12 detector. Option 3 requires the least amount of time and resources to support RGH physics program.

2. Theory

Throughout the experiment, I studied the occupancy in the Drift Chambers (DC) of the CLAS12 detector. The Drift Chambers are large boxes containing 12 layers and 112 wires. This adds up to 1,344 cells located in each of the three regions of DC in the CLAS12. Each region is divide into six sectors. DC are filled with a gas mixture of argon and carbon dioxide. The wires inside DC are ran at high voltage with some being positively charge and negatively charged. As particles pass through DC they can leave behind electrons. The electrons are attracted to the wires with the positive charge. These interactions are recorded by a computer.

Occupancy is the measurement of the number of particle interactions per detector cell per an event:

$$Occupancy \equiv \frac{N_{hits}}{N_{events} N_{cells}} \tag{1}$$

where

$$N_{hits} \equiv \text{The number of DC wires intersected by primary and secondary events throughout DC} \tag{2}$$

$$N_{event} \equiv \phi \cdot Prob(interacting) \tag{3}$$

$$\phi \equiv \text{Number of incident particles} \tag{4}$$

$$N_{cells} \equiv 112 \frac{wires}{layer} \cdot 12 \frac{layers}{wire} \tag{5}$$

To properly run the simulations, the desired luminosity, L, must be known:

$$L = N_e \cdot N_p \tag{6}$$

Where N_e = number of electrons and N_p = number of protons. Since the current, I, of the CLAS12 is defined in the simulations by an input of number of particles, charge of particles, and time:

$$N_e = \frac{1}{|q_e|} \cdot I \tag{7}$$

where

$$I = \frac{n_e \cdot |q_e|}{\triangle t} \tag{8}$$

$$N_p = \frac{n_p \cdot N_A}{M} \cdot (l\rho) \tag{9}$$

where n_p is the number of protons, N_A is Avogadro's constant, M is the molar mass of target, l is the length of the target, and ρ is the density of the target. Generally $\frac{n_p}{M} \approx 1$. For targets that have more than a single proton, n_p can be interchanged with the number of nucleons, n_N. Therefore, equation 9 becomes:

$$N_p = N \cdot l\rho \tag{10}$$

where $N = 6.022 \cdot 10^{23} mol^{-1}$. Therefore, equation 6 becomes:

$$L = \left(\frac{1}{|q_e|} I\right)(Nl\rho) \tag{11}$$

3. Methods

The simulations were ran using GEANT[4] Monte Carlo, GEMC, Root. GEMC simulates the passage of particles through materials. The ClAS12 configuration was modified using GEMC gcards, which are separate files that the simulation reads. All simulations were run remotely at the Jefferson Lab Computing Farm. There where three phases in the this experiment:

(1) GEMC Testing Phase
(2) Field Testing Phase
(3) Production Phase

During the testing phase, I used known results from the Run Group A (RGA) Fall 2018 experiments to test my accuracy while running simulations. I mimicked the instructions given by Dr. Maurizio Ungaro [**6**]. In the RGA Fall 2018 experiments liquid hydrogen was used as the target. The target length was $2cm$. The density of the target was $0.071 gcm^{-3}$. The current used for the simulations was $79.9nA$. PLugging these numbers into equation 11, the Luminosity is $4.2x10^{34} cm^{-2} s^{-1}$.

To correctly reproduce the results from the RGA Fall 2018 experiments, I had to add the lines LUMI_EVENT, LUMI_P, LUMI_V, LUMI_SPREAD_V, and RFSETUP. These lines let me control the luminosity, the current, beam position, beam angle, and the beam spread. Once the simulations were finished, I converted the statistics into root files. Once that was finished, the root files were compiled into one super root file. From there, I can create several types of graphs:

(1) Average Occupancy.
(2) Occupancy map.
(3) Histogram of particle origin.

(4) Histogram of particle origin by flavor.

The average occupancy plots the percentage of the occupancy vs sector for each region. Region 1 is depicted by a blue line, region 2 is depicted by the red line, and region 3 is depicted by the green lin. The desired occupancy is 5% but ideally it should be below 3%. There are two reasons why the desired is at 5%:

(1) If the occupancy exceeds 5% the life cycle of DC will be shorten due to wear and tear.

(2) Above 3% the background noise becomes too large.

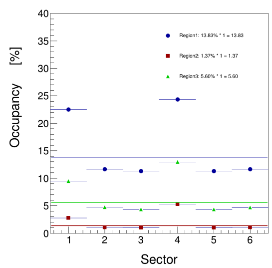


FIGURE 1. Average Occupancy

The occupancy map plots the exactly where the particle is detected and plots on a layers vs wire graph. The y-axis goes from 0-36. Layers 0-12 are region 1, layers 13-24 are region 2, and layers 25-36 are region 3. This graph can look confusing due to the disconnection in the layers but if you look at each region as its separate graph it becomes more clear.

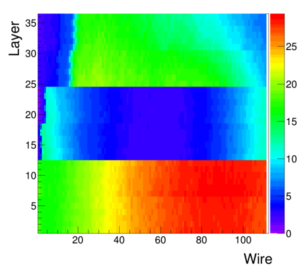


FIGURE 2. Occupancy Map

The histogram of particle origins is helpful when paired with the occupancy map. Each dot on the graph represents an order of magnitude of particles. By examining the occupancy map, you can predict which region will have the most particles. This is a “3D” image of the regions. Region 1 is the left most section starting at 1000mm extending to 3000mm, region 2 extends from 3500mm to 4500mm, and region 3 extends from 5000mm to 6000mm.

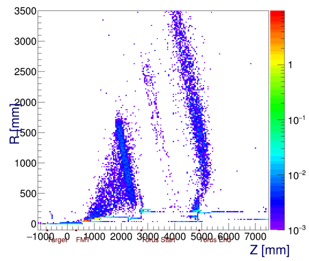


FIGURE 3. Histogram of Origins of Particles

The flavor of particles can be identified by the second type of histogram. The regions are still the same as the previous histogram. However, the particles are no longer identified by a dot, it is now identified by a line. The red line is represents an electron, the blue is gamma rays, the green is pions, the orange is protons, the yellow is other like hadrons, and the black is all.

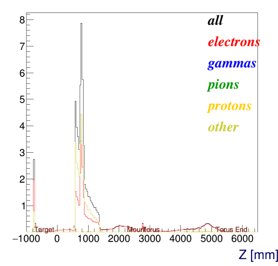


FIGURE 4. Histogram of Origins of Particles by Flavor

The next phase of the experiment was testing the transverse field. Using the RGA Fall 2018 gcard as a template, I removed lines in the gcard getting rid of:

(1) The Forward Tagger.
(2) The Central Detector.
(3) The Moller Shielding.
(4) Replaced old longitudinal field with a transverse field.
(5) Replaced liquid hydrogen target with a 60% NH_3 and 40% He target.

The parts were removed to prevent any interference in the occupancy detected in DC. The target specifications that were used from here on out are:

- $I = 0.16nA$
- $\rho = 0.578gcm^{-3}$
- $l = 2.5cm$

Plugging these numbers into equation 11 we get the desired Luminosity $\approx 10^{33} cm^{-2} s^{-1}$. I ran simulations using Dr. Ungaro's code. The only lines I needed to adjust was the path to my new gcard, the number of events, and the number of jobs. For consistency, all following gcards used the same numbers:

- Number of events = 11. Through trial and error, I found this was the most efficient amount amount of events. It did not overload the memory required
- Number of jobs = 3000. This was to ensure that I got enough statistics.

For each gcard I needed to run a graphical user interface to investigate the beam angle to ensure that the beam reached the target directly. I had to adjust the inputs in LUMI_P and BEAM_P in the gcard.

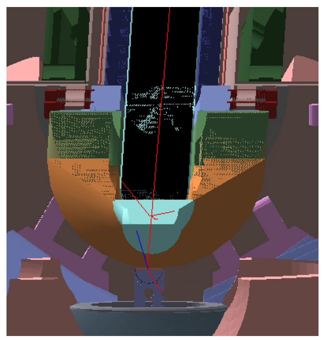
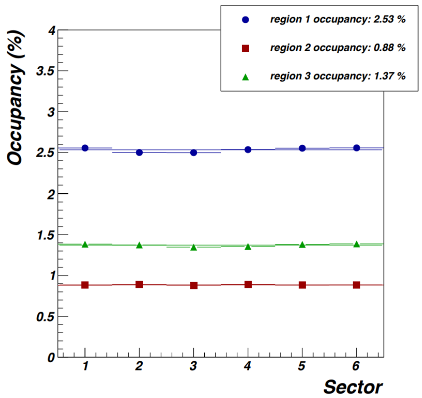


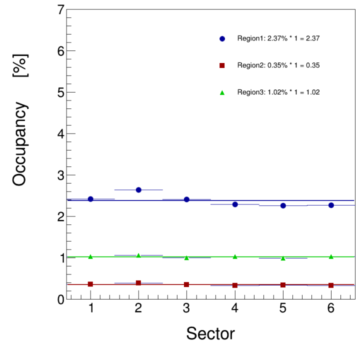
FIGURE 5. Screenshot of Beam reaching the target

After the results came back from field testing simulations, I was able to identify which sectors had the highest occupancy. The next steps were to test option 2 and option 3. I added the Run Group C moller cone, ELMO, back in. I created two gcards one with the target located at $(0, 0, 0)\, cm$ and the other located at $(0, 0, -75)\, cm$. For the target at nominal position I found the beam position to be at $(-3.5, 0, -90)\, cm$ and $(-3.5, 0, -165)\, cm$ for the target shifted 75cm away from the CLAS12 detector. I the beam angle for each gcard to be $\theta = 2.15°$ and $\phi = 0°$ in azimuthal coordinates. Both of these were done in the GUI by adjusting them slowly until the beam reached the target without interference. I ran both simulations at the aforementioned specifications. I generated the graphs by following Dr. Ungaro's code. There were only a few edits needed:

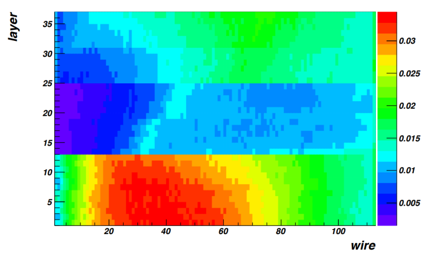
- Changing the path to the root files.
- adding a code to create a graph for a specific sector.
- adjusting the scales of the graphs and tags for target at different locations.



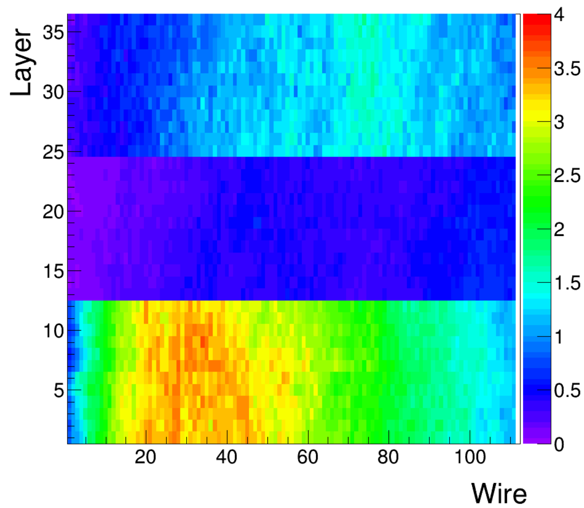
(A) Original: Average Occupancy



(B) Reproduction: Average Occupancy



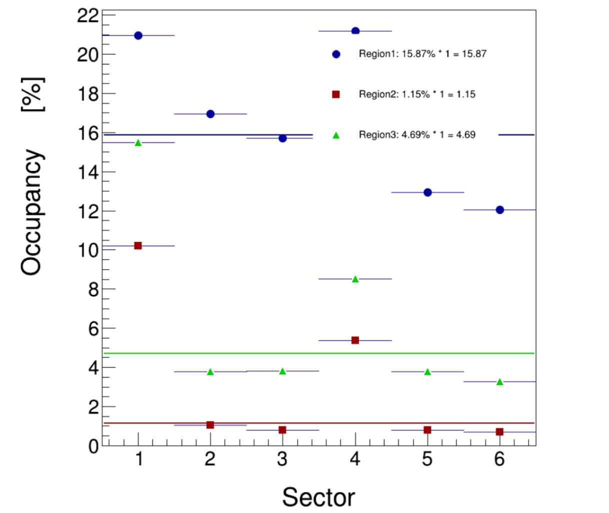
(C) Original: Occupancy Map



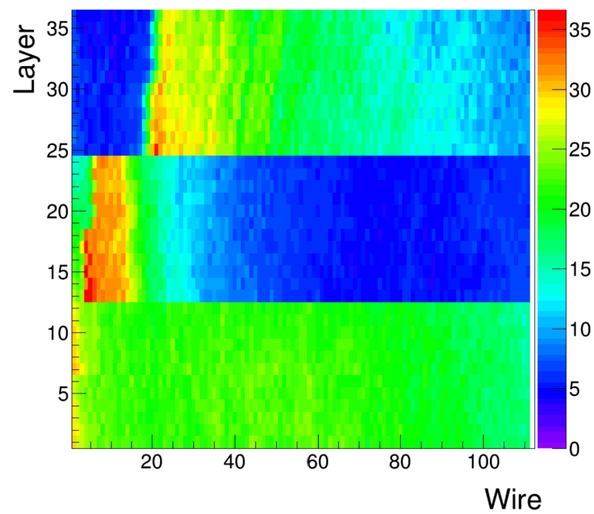
(D) Reproduction: Occupancy Map

Figure 6. Reproduction of RGA Fall 2018 Experiments

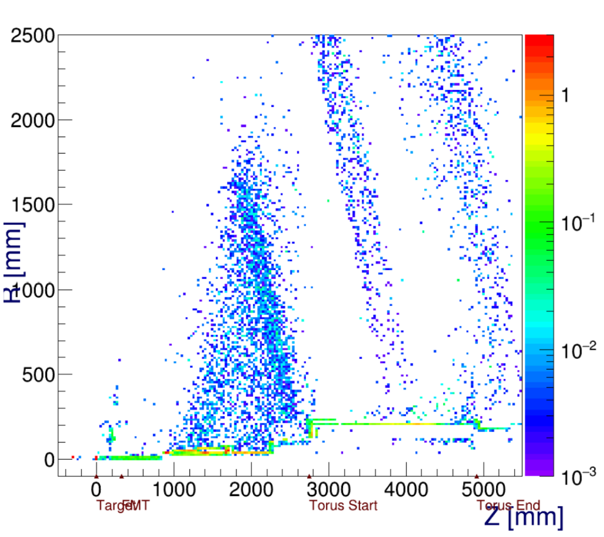
These Graphs agree with each other. These results showed competency when running the simulations using GEMC. The slight differences in the occupancy maps are due to the scales in both but they still agree with each other. The patterns are still the same.



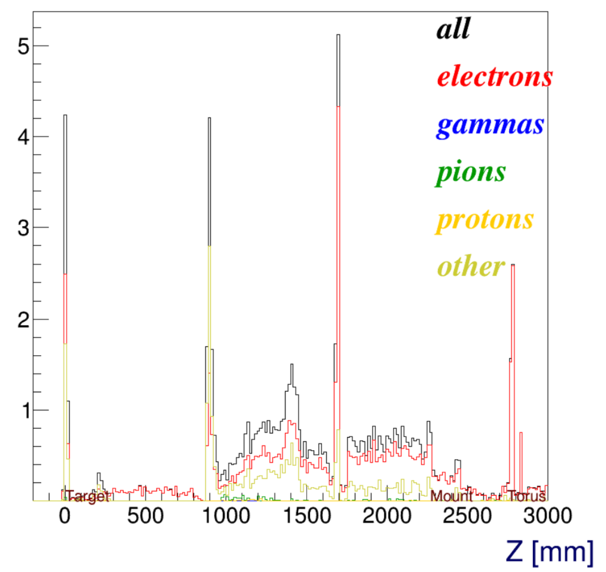
(A) Average Occupancy



(B) Occupancy Map



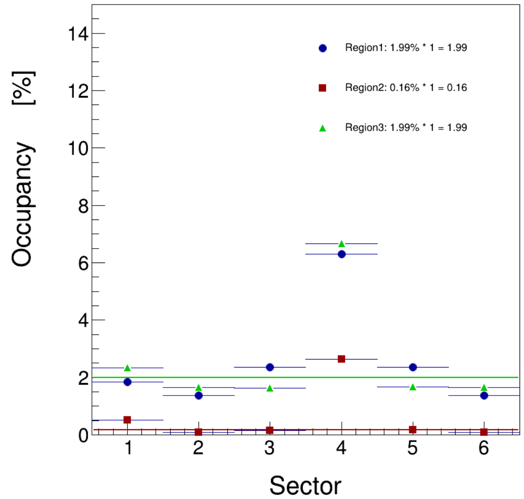
(C) Histogram of Particle Origin



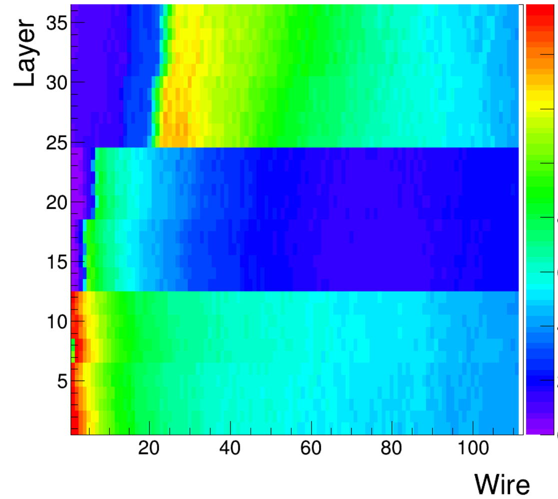
(D) Origin by Particle Flavor

Figure 7. Transverse Field Testing; Target is 60% NH_3 and 40% He; Luminosity ≈ $10^{33} cm^{-2} s^{-1}$; No Forward Tagger, No Central Detector, No Moller Shields

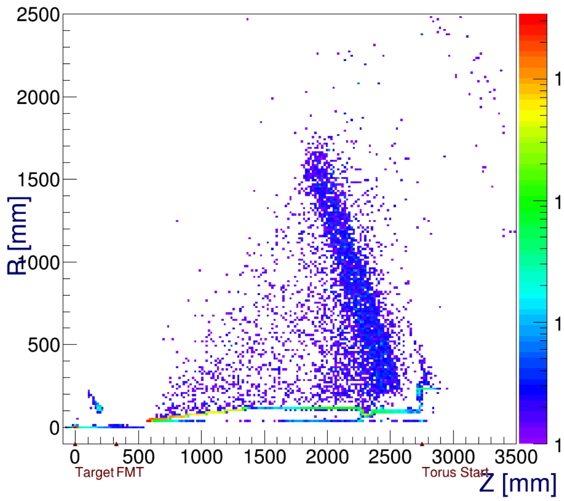
When testing the transverse field we identified that the major sectors affected by the transverse field were 1 and 4. This makes sense because of the symmetry of the sectors. Sectors 1 and 4 couple together, Sectors 2 and 6 couple together, and sectors 3 and 5 couple together.



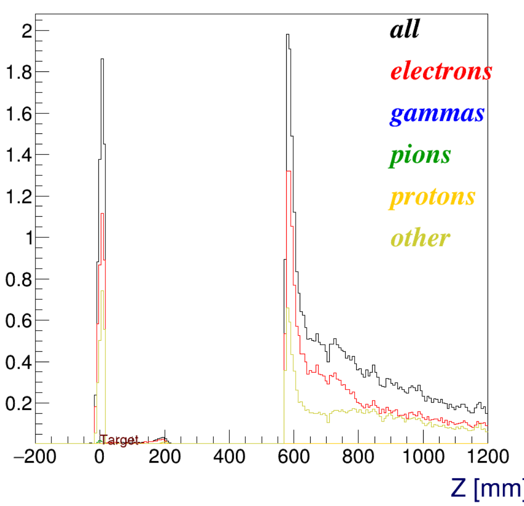
(A) Average Occupancy



(B) Occupancy Map



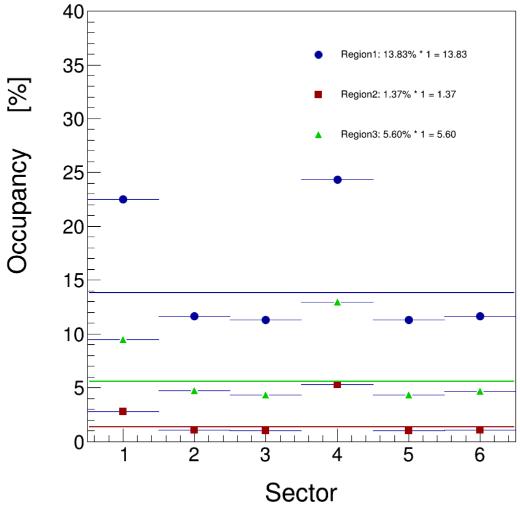
(C) Histogram of Particle Origin



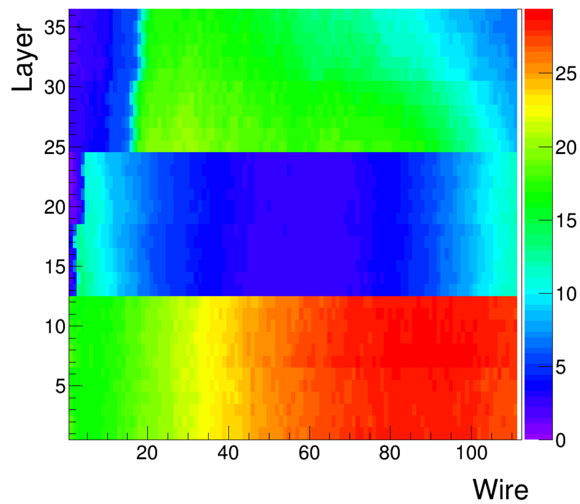
(D) Origin by Particle Flavor

FIGURE 8. Transverse Field; Target is 60% NH_3 and 40% He; Luminosity $\approx 10^{33} cm^{-2} s^{-1}$; No Forward Tagger, No Central Detector, ELMO, Target at (0,0,0)cm; Sector 4

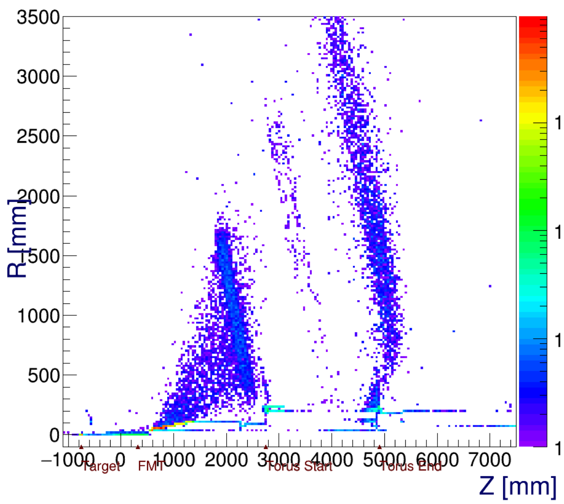
When adding ELMO back into the CLAS12 configuration, the occupancy was reduced overall. All sectors are reduced down below the ideal occupancy average of 3%. However, sector 4's occupancy is still too high. It is subjected to excess noise in the data.



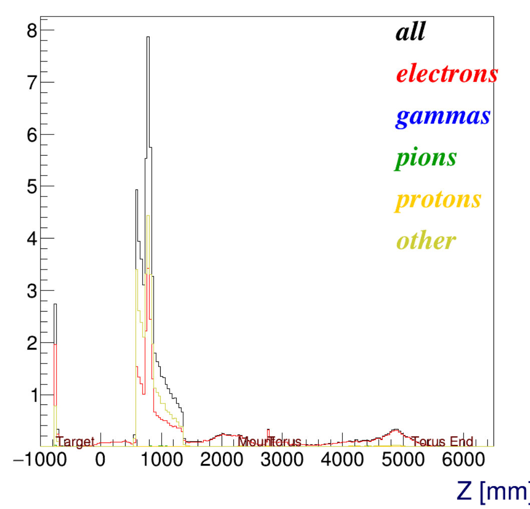
(A) Average Occupancy



(B) Occupancy Map



(C) Histogram of Particle Origin



(D) Origin by Particle Flavor

FIGURE 9. Transverse Field; Target is 60% NH_3 and 40% He; Luminosity $\approx 10^{33} cm^{-2} s^{-1}$; No Forward Tagger, No Central Detector, ELMO, Target at (0,0,0)cm; Sector 4

Originally option 3 was considered the best option because it was easiest to predict due past experiments done by Jefferson Lab even though the CLAS12 is not currently equipped for option 3. However, the results show that the occupancy is much higher in region 1 and 3.

5. Discussion and Conclusion

When analyzing the data, I expected that region 1 would have the highest occupancy rates. It is closest to the target and where the scattering particles will be deflected to. It is typical of region 2 to have the lowest occupancy rate because of its vicinity to the torus magnet of the CLAS12 detector. The magnetic field created by the torus magnet. It interferes with the particles. Since, region 3 is outside of the torus magnet the occupancy rates increase again. My results show that this is still the case after making the changes to the CLAS12 configuration.

When comparing the occupancy from both configurations where the target is at nominal position and shifted 75cm away from the detector, it is apparent that the occupancy rate is higher in the option 3. The average occupancy for region 1 is 13.83%, 1.37% for region 2, and 5.60% in region 3. In region 1, the CLAS12 cannot properly run at low luminosities without significant noise in the data. It will also decrease the lifespan of each sector in region 1. Region 2's occupancy rate is low enough but sector 4 is still too high. In region 3, sector 1 and 4 are also too high but the rest are within reason. The occupancy map shows that all wires are in region one are experience a lot of activity. Where region is relatively low except for wires 5-10 and wires 100-112. In region 3, wires 20-100 are also have a lot of measured occupancy. The histograms show that region 1 and 3 have a lot of detected particles. The flavor of particles are indicated heavily by the other line, which include hadrons. This is expected because of the transverse field.

The occupancy is much lower when the target was at nominal position. The average occupancy rate was at 1.99% region 1 and region 3. In region 2 the occupancy was at 0.16%. In sectors 1, 2, 3, 5, and 6 for all regions, they are well below the ideal occupancy rate of 3%. In sector 4 the occupancy rate is higher than 5% in region 1 and 3 but not in region 2 which means there is still too much activity in region 1 and 3. However, these results are promising. Only losing one sector is a vast improvement from the transverse field testing and shifting the target $(0, 0, -75)\, cm$.

Even though option 3 was the originally predicted as the most promising, option 2 is being further investigated because of its lower occupancy rates. It shows more promise than originally thought. The next steps Jefferson Lab will take is adding all of the original parts back into the CLAS12 and running more simulations. I will be tasked with those simulations.

6. Appendices

Edited Code: RGA added LUMI in gcard

- ```
  <!--  RF Signal needs event time window defined by LUMI_EVENT -->
  <option name="LUMI_EVENT"     value="124000, 248.5*ns, 4*ns" />
  <option name="LUMI_P"         value="e-, 10.6*GeV, 0*deg, 0*deg" />
  <option name="LUMI_V"         value="(0.0, 0.0, -10)cm" />
  <option name="LUMI_SPREAD_V"  value="(0.03, 0.03)cm" />
  <option name="RFSETUP"        value="0.499, 40, 20" />
  ```

Edited Code: Transverse Field Testing

- Removing equipment by deleting lines

```
<detector name="experiments/clas12/ft/ft" factory="TEXT"       variation="FTOff"/>
<detector name="experiments/clas12/beamline/cadBeamlineFTOFF/" factory="CAD"/>
<detector name="experiments/clas12/beamline/beamline"      factory="TEXT" variation="FTOff"/>
<detector name="experiments/clas12/beamline/vacuumLine/"       factory="CAD"/>
<detector name="experiments/clas12/ftof/ftof"   factory="TEXT" variation="rga_fall2018"/>
<detector name="experiments/clas12/ec/ec"      factory="TEXT" variation="rga_fall2018"/>
<detector name="experiments/clas12/pcal/pcal"      factory="TEXT" variation="rga_fall2018"/>
<detector name="experiments/clas12/ltcc/ltcc"      factory="TEXT" variation="rgb_spring2019"/>
<detector name="experiments/clas12/ltcc/cad_cone/"     factory="CAD"/>
<detector name="experiments/clas12/ltcc/cad/"          factory="CAD"/>
```

- Editing LUMI

  ```
  <!--  RF Signal needs event time window defined by LUMI_EVENT -->
  <option name="LUMI_EVENT"     value="252, 252*ns, 4*ns" />
  <option name="LUMI_P"         value="e-, 10.6*GeV, 215*deg, 0*deg" />
  <option name="LUMI_V"         value="(-3.5, 0.0, -90)cm" />
  <option name="LUMI_SPREAD_V"  value="(0.05, 0.05)cm" />
  <option name="RFSETUP"        value="0.499, 40, 20" />
  ```

- Matching Beam conditions with Lumi conditions:
  ```

```
    <!-- beam conditions -->
<option name="BEAM_P"    value="e-, 10.6*GeV, 2.15*deg, 0*deg"/>
<option name="BEAM_V"    value="(-3.5, 0, -90)cm"/>
<option name="SPREAD_V"  value="(0.05, 0.05)cm"/>
```

- Changing field:

```
        <!-- you can scale the fields here. Remember torus -1 means e- INBENDING  -->
<option name="SCALE_FIELD" value="TorusSymmetric, -1"/>
<option name="SCALE_FIELD" value="transverseNewMagnet, 1.0"/>

<!-- hall field  -->
<option name="HALL_FIELD"    value="transverseNewMagnet"/>
<option name="DISPLACE_FIELDMAP" value="transverseNewMagnet, 0*cm, 0*cm, 0*cm" />
<option name="ROTATE_FIELDMAP"   value="transverseNewMagnet, 0*deg, 0*deg, 0*deg" />
```

Edited Code: Option 2

- Field is the same as the transverse field testing
- beam conditions and LUMI conditions are the same as Transverse field testing
- changed target to NH_3

```
         <!-- target. Notice variation give the target type. Can be: lH2, lD2, ND3 -->
<detector name="experiments/clas12/targets/transverseTargetCad/" factory="CAD"/>
<detector name="experiments/clas12/targets/target" factory="TEXT" variation="transverse"/>
```

- Adding in ELMO:

```
        <!-- Beamline configuration: ELMO is used -->
<detector name="/experiments/clas12/beamline/cadBeamlineELMO/" factory="CAD"/>
<detector name="/experiments/clas12/beamline/vacuumLine/"  factory="CAD"/>
<detector name="/experiments/clas12/beamline/beamline"     factory="TEXT" variation="ELMO"/>
<detector name="connectUpstreamToTorusPipe">
<existence exist="no" />
</detector>
```

- Added physics line for Dr. Harut Avakian:

```
<option name="PHYSICS" value="FTFP_BERT + STD + Optical"/>
```

- Edited print event to allow the root files to be created regardless of event setting in Master

```
        <!--  Will print message every 10 events -->
<option name="PRINT_EVENT"    value="1" />
```

Edited Code: Option 3

- Option 2 gcard was used as a template for option 3.
- Shifted target

```
        <!--  Reference position set as target shift below -->
<option name="RFSTART"     value="eventVertex, 0, 0, -75.0" />
```

- Shifted magnetic field in Beam conditions and LUMI conditions

```
<option name="BEAM_V"    value="(-3.5, 0, -165)cm"/>
<option name="LUMI_V"         value="(-3.5, 0.0, -165)cm" />
```

Editing code for graphs

- Added line in init.C to change the sector for graphs; sectors range from 1-6

```
hitCutR += " && sector==3";
```

References

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