POSITION RESOLUTION OF THE DETECTION SYSTEM OF THE
OUT-OF-PLANE SPECTROMETER

by

DAVID A. TOBACK

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ABSTRACT

We determined that individual planes in the Horizontal Drift Chambers used in the Out-Of-Plane Spectrometer have an average position resolution of 174±9μm FWHM. This result, the first of its kind at sea level, is consistent with that reported by Los Alamos. We also determined that the chamber resolution is unaffected by the rate at which particles are detected and is uniform as a function of chamber position. This thesis also describes the methods for obtaining optimal particle path reconstruction in software and for dealing with multiple scattering effects.

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1. Introduction

The Out-Of-Plane Spectrometer (OOPS) is designed to help perform electron-proton coincidence experiments at the Bates Linear Accelerator Center in Middleton, MA. The design, assembly and testing of this proton spectrometer is largely the responsibility of a collaboration between the Massachusetts Institute of Technology under Prof. William Bertozzi and the University of Illinois at Urbana-Champaign under Prof. Costas Papanicolas. When completed, the first OOPS will be used with the Energy Loss Spectrometer SYstem (ELSSY) in d(e,e'p) experiments to determine the transverse and longitudinal response functions of the deuteron. Later, the OOPS will be used as the model for three others OOPS's which, because of their small weight and compactness, will be mounted out of the electron scattering plane and used in conjunction with the One Hundred Inch Proton Spectrometer (OHIPS) on N->Δ experiments to determine the other deuteron response functions.

According to scattering theory\(^1\), the cross section for the deuteron is given by the equation
\[
\frac{d\sigma}{d\Omega_{\text{Elect}}d\Omega_{\text{Prot}}d\omega_{\text{Elect}}dE_{\text{Prot}}} = \sigma_{\text{Mott Cross Section}} \left[ V_{\text{LT}} R_{\text{LT}} + V_{\text{LT}} R_{\text{LT}} \cos\phi + V_{\text{LT}} R_{\text{LT}} \cos 2\phi \right]
\]
where the \(V\)'s are the electron kinematic functions, the \(R\)'s are the electron response functions, the \(L\) and \(T\) subscripts stand for longitudinal and transverse respectively and \(\phi\) is the angle out of the scattering plane. If a beam of polarization \(P\) is used, then a \(P_e V'_{\text{LT}} \vec{R}_{\text{LT}} \sin\phi\) term is also added. In

\(^1\) H. Arenhövel, On Deuteron Breakup by Electrons and the Momentum Distribution of the Nucleons in the Deuteron, Nuclear Physics A384 (1982) Pages 287-301
the first experiment the OOPS will be placed in a position such that the outgoing proton will be detected in a direction parallel to \( \vec{q} \). This setup takes advantage of the fact that in parallel kinematics \( \phi \) is zero and the \( V_{LT}, V_{TT} \) and \( V_{LT}' \) terms are identically zero which means that \( R_L \) and \( R_T \) can be determined. In the later experiments with OHIPS, the four OOPS modules will be placed out of the scattering plane and thus it is possible to determine \( R_{LT}, R_{TT} \) and \( \tilde{R}_{LT} \).

The OOPS itself, shown in figures 1a and 1b for both experimental assemblies, consists of a pair of magnets (a dipole and a quadrupole), the detector package, collimators, four inches of lead shielding near the detector package and a vacuum system. The magnets of the OOPS can provide fields of 8kG, allowing a central momentum of 850 MeV/c with an acceptance of about \( \pm 5\% \) and have a dipole-quadrupole configuration which gives the focal plane a tilt of 17.5°. The magnets further permit maximal acceptances of \( \Delta \Theta = \pm 31 \text{mr} \) and \( \Delta \Phi = \pm 11 \text{mr} \), where \( \Theta \) and \( \Phi \) are angles as defined by the Transport coordinate system, see figure 2. The support structure of the OOPS, also shown in figure 1, allows the OOPS to be mounted independent of module orientation and thus out of plane.

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2 K.L. Brown, F. Rothacker, D.C. Carey, Ch. Iselin, TRANSPORT: A Computer Program for Designing Charged Particle Beam Transport Systems, SLAC-91, Rev. 2 UC-28 (I/A)
Figure 1a shows a single OOPS module shown in its mechanical structural support. Figure 1b shows the experimental setup for the 4 OOPS modules, oriented symmetrically about the Q axis, and OHIPS. Also shown in figure b is the scattering chamber and the beam line. Courtesy of Steve Deoifini and the University of Illinois.
Figure 2) Transport coordinate system. The X-Z plane corresponds to the bend plane of the dipole. In this system, shown in figure 2, Z is the direction of the central ray, \( \Theta \) is defined as the angle in the direction of bend from the central ray, and \( \Phi \) is defined as the angle which completes the orthogonal coordinate system.

Over the last few years the body of the prototype OOPS was constructed by the group from the University of Illinois. Concurrently, the detection and data acquisition systems were built by the group from MIT. During the summer of 1990, this construction was completed and preliminary testing was done at Bates. The first d(e,e'p) RL/RT separation is scheduled for the Winter of 1991 and following this experiment, final testing and optimization will be done and the three other spectrometers will be constructed using the modified OOPS as a model.

This thesis reports on the resolution of the MIT built OOPS detector package using electron scattering data from the two 1990 summer test runs. It begins with a description of the package itself and then outlines the position determination in an individual Horizontal Drift Chamber. It then continues by describing the procedure for determining particle trajectories through the package as well as optimizing the path reconstruction. Finally, the process of determining the individual chamber resolution is given along with the results.
2. Physical Description of the Detector Package

The OOPS detector package, as shown in figure 3, consists of three horizontal drift chambers (HDC) and three scintillators. The accompanying electronics setup, which consist of standard TDCs and ADCs and some custom designed (labeled Odd-Even) amplifiers, is shown in figure 4 and is coupled to the Q data acquisition system\(^3\).

Figure 4 shows how the scintillators are used for timing purposes. A trigger is formed by a coincidence of each of the six signals sent from two sides of the three scintillators. The timing of this trigger, which is used to start the TDCs, is determined by the middle scintillator, L2. The scintillators themselves were modeled after those used in the OHIPS spectrometer at Bates\(^4\) and have an active area of 7in by 17in. The three scintillators have different thickness, 1/16in, 3/16in and 3/16in for scintillators 1, 2 and 3 respectively, with reference to the figure. These thicknesses were chosen to permit rejection of a \(\pi^+\) background as a \(\pi^+\) will deposit less energy than a proton and can be rejected in hardware or software. Flexible optic fiber light guides were used to allow the scintillator package to fit inside the small space for the detection system.

\(^3\) The Q data acquisition was created at the Clinton P. Anderson Meson Physics Facility (LAMPF) Group MP-1. See supporting documentation.

Figure 3) Arrangement for the Horizontal Drift Chambers and Scintillators in the OOPS detector package. The detector package is viewed from two different angles, and the particle path is from the front to the rear. The chambers are labeled C1, C2, and C3, and the scintillators are labeled S1, S2, and S3. Courtesy of Steve Dolfini and the University of Illinois.
Figure 4) Electronics Setup for the OOPS. This is coupled to the Q data analysis system at the Bates Linear Accelerator Center. Downstairs refers to the electronics inside the OOPS itself and Up-stairs refers to the electronics inside the North Hall counting bay. Courtesy of Maurik Holtrop and MIT.
Each HDC contains two individual detection planes, one for vertical position and one for horizontal position, X and Y in the Transport coordinate system. Their design, construction and operating parameters are similar to those used in the EPICS and HRS spectrometers at Los Alamos\textsuperscript{5}. Each HDC is roughly 4.0 cm thick and contains eight 0.48 cm thick aluminum plates which support the alternating wire and cathode planes, see figure 5a. The gas mixture inside the HDC is 65% Argon, 35% Isobutane and 0.5% alcohol and is kept at vapor pressure at ~35\degree. The two wire planes, X and Y, contain 21 and 38 parallel wires respectively. These planes are separated by grounded cathode planes consisting of 0.25 mil Aluminized Mylar. Each wire plane contains two types of wire, anode wires (20 \mu m gold-plated tungsten) which are kept at a positive potential of approximately 2500V*, and ground wires (76 \mu m gold-plated copper-clad aluminum) which are kept at zero potential. These wires are arranged as in figure 5b with the two types alternating (anode wire, potential wire, anode wire etc.) and an interwire spacing of 4 mm. This gives a 0.8 cm separation between anode wires and a total active area of roughly 17 cm x 32 cm.


* The anode voltage used is higher than that used at Los Alamos because atmospheric pressure at sea level causes the gas density to be higher. Thus the electron mean free path in the gas is smaller and higher anode voltages are required as there is less time for the electron to gain enough energy to cause the avalanche necessary to cause a strong signal.
Figure 5a) This figure shows the overall plane structure of the Horizontal Drift Chambers.

- Anode Wires
- Ground Wires

Figure 5b) Schematic arrangement of cathode plane and wire plane in a HDC.
The equipotential lines of an example anode plane immersed in a gas mixture are shown in figure 6. As a charged particle passes through the gas, electrons, knocked out along the ionization track, drift along an electric field line to the nearest anode wire. Near the anode wire the electric field goes as $1/R$ and the electron is able to gain enough energy between collisions to cause an ionization avalanche. This is collected by the anode wire and forms a signal which travels along an internal common delay line to capacitors at either end. These signals form the stops for two TDCs measuring the elapsed times between the scintillator trigger and the delay line signal.

The avalanche is generally localized to one side of the anode wire. The two adjacent ground wires collect the positive ions and send an induced signal to two separate bus lines. These small signals then travel to a special odd-even amplifier which outputs the analog pulse height difference and sum, again see figure 4. The odd-even difference signals are measured by ADCs, and using these signals, as well as those from the TDCs, we can determine the position of particle intersection. How these calculations are done is the subject of the next section.

![Diagram of equipotential lines in an HDC](image)

*Figure 6* Typical equipotential lines in a HDC - Taken from A.H. Walenta Nucl. Instr. and Meth. 151 (1978) 461 - 472
3. Procedure

A. Chamber Calibration and Position Determination

We can find the point where the particle path intersected the HDC by taking the position of the anode wire that fired the delay line and adding or subtracting the drift distance to that wire. Whether the drift distance is added or subtracted is determined by which side of the wire the particle passed. This position determination as well as the chamber calibration follows the discussion in Atencio\textsuperscript{6} and will be restated and elaborated upon here.

We define the overall corrected position by the equation

$$X_{Corrected} = X_{Truncated} \pm X_{Drift}$$

$X_{Truncated}$ can be calculated from the TDC time values because there is a fixed delay time between wires along the delay line in the HDC. Assuming there is no dispersion along the delay line, the amount of time elapsed when the signal reaches each end of a delay line is given by:

$$T_{Left} = (n-1) \Gamma + T_d + C$$
$$T_{Right} = (N-n) \Gamma + T_d + C'$$

where $n$ is the wire number, $N$ is the total number of wires, $\Gamma$ is the delay time between wires, $T_d$ is the drift time to the anode wire and $C$ and $C'$ are constants proportional to the length of the cables to each TDC. Solving these equations for $n$ gives the wire position.

$$n = \frac{1}{2\Gamma}(T_{Left} - T_{Right} + (N + 1)\Gamma) + C''$$

where $C''$ is easily subtracted off as it is constant for every event.


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because the combined total cable length to the TDCs is constant. Unfortunately, the time it takes the particle to travel from the HDCs to the scintillators as well as the amount of time it takes a scintillator to generate a signal for the TDCs cause timing imperfections (this second effect is much larger and will be discussed later). Since the wire number is a function of the timing difference

\[ T_- = T_{\text{Left}} - T_{\text{Right}} \]

we can very accurately approximate the wire position by

\[ X_{\text{Untruncated}} = A_2 T_-^2 + A_1 T_- + A_0 \]

where the quadratic term accounts for dispersion along the long delay lines and the \( A_i \) are coefficients that convert the time to a distance.

Since the spacing between the anode wires is a known quantity we can determine and optimize these coefficients by using the function

\[ X_{\text{Truncated}} = \text{nint} \left( \frac{X_{\text{Untruncated}}}{d_{\text{Wire}}} \right) d_{\text{Wire}} + O_{\text{Truncated}} \]

where

\[ d_{\text{Wire}} = \text{Physical spacing between anode wires} \]

and the nint function chooses the the nearest integer and \( O_{\text{Truncated}} \) is an offset that is later used to fix the zero of the coordinate system. We determine the coefficients \( A_i \) by minimizing the chi squared function

\[ X^2 = \sum_{i=1}^{n} (X_{i, \text{Untruncated}} - X_{i, \text{Truncated}})^2 \]

where \( n \) is the number of particles that passed through the chamber. The values used in this experiment are shown in Table 1. Note the small value of \( A_2 \).
Once the coefficients have been determined we get a spectrum like that shown in figure 7a. As seen in the figure, these peaks have a finite width and a number of events do not clearly fall in either peak. By using the function, $X_{\text{Truncated}}$, we can get a best guess as to which wire was triggered. An example of an $X_{\text{Truncated}}$ spectrum is shown in figure 7b for the Y-Plane.

Both figures 7a and b are histograms of events which require a good signal from all the chambers and scintillators. This data was taken for electrons with a carbon target and a high incident rate. All subsequent figures, unless otherwise noted, are taken from this run and have the same requirements. These runs, despite the cuts, yield high statistics $\sim 84,000$ good events.

<table>
<thead>
<tr>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>1.010</td>
<td>1.528</td>
<td>1.311</td>
<td>1.288</td>
<td>1.253</td>
</tr>
<tr>
<td>A1</td>
<td>.04126</td>
<td>0.4241</td>
<td>.04295</td>
<td>.04548</td>
<td>0.4476</td>
</tr>
<tr>
<td>A2</td>
<td>-6.202*10^{-6}</td>
<td>-1.55010^{-6}</td>
<td>-5.98810^{-7}</td>
<td>-1.02810^{-6}</td>
<td>-3.60210^{-6}</td>
</tr>
</tbody>
</table>

Table 1) This table lists the values of the coefficients used to calibrate the X and Y plane. A0 is in units of cm, A1 in units of cm/TDC channel, A2 in units of cm/(TDC channel)$^2$ and one TDC channel = 250 picoseconds (250*10^{-12}sec)
Figure 7a  Untruncated Position Spectrum

Figure 7b  Truncated Position Spectrum
The next step is calculating the drift distance to the anode wire. Unfortunately, the electric fields inside the plane are not constant. This causes the velocity of an ionized electron to increase as it gets closer to the anode wire. Thus, electrons ionized by a particle that passed close to the sense wire will have a higher average velocity that that due to a particle that passed further away from the sense wire. Consequently, drift times are not linearly related to drift distances and a look-up table must be used.

Using the TDC information and solving we first find \( T_{\text{Drift}} \) according to the equation

\[
T_{\text{Drift, ideal}} = \frac{1}{2}(T_{\text{Left}} + T_{\text{Right}} - (N - 1)\Gamma)
\]

Again, timing imperfections modify this relationship slightly, so we make the approximation

\[
T_{\text{Drift}} \sim T_{\text{Left}} + T_{\text{Right}}
\]

and add corrections. By adding \( O_{\text{Drift}} \), a constant correction to each individual planes, we can align the drift time spectra so that a single look up table can be used for the different planes. A further correction, \( O_{\text{Event}} \), is an event by event scintillator timing correction.

A passing particle creates a light signal in the scintillator which, after a finite amount of time, reaches the photomultiplier tubes (PMTs) at either end of the scintillator. However, for data acquisition simplicity, the timing is determined by using a signal from only one of end of the middle scintillator. This means that particles that cross the scintillator far away from that particular PMT will start the delay line TDCs later than those that pass closer to the PMT. This causing timing fluctuations in the raw data. But, by
looking at the PMTs at the two ends of the scintillator, we can calculate a mean TDC start time for each event and use it to give a more accurate drift time spectrum. Thus we get:

\[ T_{\text{Drift}} = T_{\text{Left}} + T_{\text{Right}} + O_{\text{Drift}} + O_{\text{Event}} \]

which we use to find the corresponding drift distance, \( X_{\text{From Look-up Table}} \), from the look-up table.

For the July runs, a look-up table was generated by using the knowledge that the illumination of the planes in the Y direction was nearly uniform. By taking a region that was particularly uniform and covered a distance many wires long, each drift distance is likely to have an equal number of particles travel that distance. Thus, by generating a table such that a drift time spectrum is converted to a flat histogram of drift distances, we make the correct drift time to distance conversion.

An example drift time spectrum where \( O_{\text{Drift}} \) has been set up so that the spectrum begins in a low channel is shown in figure 8a. The average spectrum quickly peaks and slowly declines, exhibiting the non-linearities in the electric field by showing more paths with shorter drift times. An example of the calculated drift position spectra is shown in figure 8b. The flatness of this plot shows that the look up is quite accurate for any one of the drift planes. Figure 8c shows the relationship between the drift time and distance and is in essence the drift time to distance conversion.
DRIFT TIME - In channels
Approximate Scale of 1 nanosecond/Channel
Figure 8a) Histogram of Drift Time Spectrum

DRIFT POSITION - Scale in channels, 100 Channels/cm
Figure 8b) Histogram of Drift Position Spectrum. Note that the spectrum is normalized to 40 mm.
DRIFT TIME - In channels
Approximate Scale of 1 nanosecond/Channel

Figure 8c) 2-D Histogram of Drift Position vs. Drift Time. This is the basis of the drift time to distance look-up table.

Left-Right Amplitude Spectrum
Arbitrary Amplitude Units

Figure 9) Example histogram of the Left-Right spectrum for the induced signals on the potential wires. Notice the clear separation. The dashed lines indicate the cut on the spectrum. In this particular example the counts between the dashed lines correspond to events that fell on the right side of the wire.
Once the wire position and drift distances have been determined the next step is making the left-right decision or, in other words, deciding whether the drift distance is added to or subtracted from the truncated distance. This decision is made using the help of the induced signals on the adjacent cathode wires, as measured in the ADC left-right difference spectrum, shown in figure 9. In this figure the two peaks represent the number of counts found on either side of the wire. The two sides are clearly separated and by placing a cut around one of the peaks we can flag those events which passed on a particular side of wire. Which side is which is then determined using two methods and is called the left-right (L-R) decision.

In the July runs there was a sharp peak in the X direction position spectrum. So, inspection of a plot of $X_{\text{corrected}}$ illustrates whether a correct L-R decision is made. If the incorrect decision is made, sharp cliffs will appear in the spectra and if it is done correctly the peaks will be smooth. Figure 10 shows plots of the incorrect and correct decision in the X direction in all three chambers.

In the Y direction, the particles had nearly parallel paths through the detection system. Thus, the Y positions will be highly correlated, and a plot of $Y_1$ vs. $Y_2$, for example, will be linear. However, if the L-R decision is not made correctly various other effects will occur. See figure 11. Once the L-R decision is made correctly, the position determination is complete. Figure 12 shows an example of $X_{\text{Corrected}}$ for a Y-Plane.
Corrected X Position - Scale in channels, 100 Channels/cm

Figure 10a) Example histogram for corrected position in X1 (plane 1 in X direction). Here the Left-Right decision is made incorrectly.

Corrected X Position - Scale in channels, 100 Channels/cm

Figure 10b) Example histogram for X1. Left-Right decision made correctly.
Corrected X Position - Scale in channels, 100 Channels/cm
Figure 10c) Left-Right decision made incorrectly for X2.

Corrected X Position - Scale in channels, 100 Channels/cm
Figure 10d) Left-Right decision made correctly for X2.
**Figure 11a)** Plot of Y2 vs. Y3. Both Left-Right decisions made incorrectly. Consistent, but incorrect decision.

**Figure 11b)** Plot of Y1 vs. Y2. One Left-Right decisions made correctly the other incorrectly. Inconsistent decision.
Figure 11c) Plot of Y1 vs. Y3. Both Left-Right decisions made correctly. Consistent and correct decision.

Figure 12) Corrected position spectrum histogram for Chamber 1, Y-plane
B. Correct Trajectory Determination and Multiple Detector Optimization

Using plane intersection positions, we can reconstruct the particle trajectory in software using basic fitting methods. If one of the planes is physically translated or rotated relative to the others, we can make corrections in software. By translating and rotating the planes in X and Y we can align the detector package and optimize the particle path reconstruction.

In order to explain how this done, we first define the difference value:

\[ \Delta X = X_{\text{From line fit}} - X_{\text{Corrected}} \]

\(X_{\text{From line fit}}\) can be calculated using two or three chambers. If a two point fit is used, the difference is taken between the predicted and actual positions in the chamber that was not used for the fit. For example:

\[ \Delta X_{2, 2 \text{ point fit}} = X_{\text{Fit from 1 and 3}} - X_{\text{Corrected position from plane 2}} \]

A histogram of these difference values will yield, for an optimal particle path reconstruction, a peak, symmetric around zero and with a minimized width. Furthermore, when the reconstruction parameters have been optimized the difference spectrum will be independent of X and Y position, and of drift distance.

First order corrections are done by translating the six planes. In order to correctly align the chambers a slit can be used to define a central ray with small deviations, in both X and Y, thus serving as the origin. By translating each of the six planes so that the spectra center on zero we are assured good alignment. However, a finer alignment is needed to determine the resolution of an individual chamber. Since any two chambers, both X and Y in each, uniquely
determine a coordinate system, it merely suffices, for resolution purposes, to translate any one chamber with respect the other two. If the alignment is incorrect, using the two point fit, the difference spectrum will be symmetric around a value equal to that particular plane’s deviation from the coordinate system defined by the other two planes. Translating that plane equal to the deviation value the planes will be better aligned. For reasons that will be clear later, the difference spectrum from the middle plane using the two point fit yields the smallest width and so by translating this plane we can achieve a better alignment and thus determine the resolution more accurately.

Second order alignment corrections can be made if one or more chambers are rotated with respect to each other. A graph of difference spectra in one direction as a function of position in another direction will be tilted if this is the case. During the July run, there was a slight rotation, on the order of milliradians, that needed to be accounted for. The original difference spectrum for X plotted as a function of Y is shown in figure 13a. In the first plot the tilt shows the position dependence of the difference values, indicating a relative rotation. A simple rotation in the second plane corrected the problem. Figure 13b, with a blown up scale, is flat and illustrates the position independence of the difference values, thus indicating correct alignment.

Plots of difference vs. drift distance are shown in figures 14a and b. The flatness of the first plot illustrates drift time independence. It further shows that the left-right decision has been made correctly because an incorrect decision would produce tilted plots and show drift time dependence. An example of this is shown in the second figure for one left-right decision made incorrectly.
Figure 13a) Example 2-D histogram of difference in X vs. Y with incorrect chamber alignment due to rotated chamber.

Figure 13b) Example 2-D histogram of difference in X vs. Y with correct chamber alignment. Note the expanded vertical scale relative to 13a.
Figure 14a) Difference in Y vs. Drift Position. Illustrates Drift Position independent resolution.

Figure 14b) Difference in Y vs. Drift Position. Left-Right decision made incorrectly for one plane.
Figures 15a and b show ΔY vs. Y. These figures illustrate optimal path reconstruction and show that the chambers are aligned with respect to one another because there is no position dependence. Chamber translation and rotation values for our particular setup are given in Table 2. The absolute values of the translations are high because of software zeroing. The physical misalignment, which is small, can be seen in the differences between these values. The rotation correction, as mentioned before, is very small.

<table>
<thead>
<tr>
<th>Chamber Offset X1</th>
<th>1.9700 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Offset X2</td>
<td>1.1527 cm</td>
</tr>
<tr>
<td>Chamber Offset X3</td>
<td>1.3140 cm</td>
</tr>
<tr>
<td>Chamber Offset Y1</td>
<td>-1.1200 cm</td>
</tr>
<tr>
<td>Chamber Offset Y2</td>
<td>-1.0641 cm</td>
</tr>
<tr>
<td>Chamber Offset Y3</td>
<td>-1.0120 cm</td>
</tr>
<tr>
<td>Chamber 1 Rotation</td>
<td>0</td>
</tr>
<tr>
<td>Chamber 2 Rotation</td>
<td>3.8 mRadian</td>
</tr>
<tr>
<td>Chamber 3 Rotation</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2) Table of Chamber Rotations and Translations used for reconstruction optimization
Corrected Y Position - Scale in channels, 100 Channels/cm

Figure 15a) Example 2-D histogram for difference in Y vs. Y. Illustrates position independent resolution and optimized path reconstruction.

Corrected Y Position - Scale in channels, 100 Channels/cm

Figure 15b) Example 2-D histogram for difference in Y plotted against position in Y, larger scale.
C. Theoretical Intrinsic Chamber Resolution Calculations

Using the difference spectrum from the two and three point fittings we determined the intrinsic chamber resolution. With a correct path reconstruction, the error, or spread, in the difference spectrum comes from the intrinsic resolution limitations of the individual chambers and from the particle multiple scattering in the detector package. If the chambers are labeled A, B and C respectively, then the spread due to the intrinsic resolution of the chambers is $\Delta A = \Delta B = \Delta C = \Delta_{\text{chamber}}$. However, $\Delta C$ needs to be corrected to take the multiple scattering into account. This is because if the scattering takes place in the first or third chambers the particle trajectory will still be a straight line through the detection system. If the scattering occurs in chamber two, the effect will be noticed in chamber three and will thus contribute to the difference spectrum spread. Thus, following Bevington\(^7\)

$$\Delta C_{\text{Corrected}}^2 = \Delta C^2 + \Delta_{\text{Multiple Scattering FWHM}}^2$$

If the difference is calculated using only two planes then

$$\text{Diff}_B = B_{\text{Fit}} - B_{\text{Exp}} = \frac{A + C}{2} - B$$

$$\text{Diff}_A = \text{Diff}_C = 2B - A - C$$

where A, B and C are the measured positions in chambers A, B and C respectively. Then,

---

\[ \sigma_B^2 = \left( \frac{1}{2} \Delta A \right)^2 + \Delta B^2 + \left( \frac{1}{2} \Delta C_{\text{corrected}} \right)^2 \]

\[ = \frac{1}{4} \Delta_{\text{Chamber}}^2 + \Delta_{\text{Chamber}}^2 + \frac{1}{4} \left( \Delta_{\text{Chamber}}^2 + \Delta_{\text{MS}}^2 \right) \]

\[ = \frac{3}{2} \Delta_{\text{Chamber}}^2 + \frac{1}{4} \Delta_{\text{MS}}^2 . \]

where \( \sigma_B \) is the FWHM of the experimentally determined \( \text{Diff}_B \) spectrum.

Solving for the intrinsic chamber resolution we get

\[ \Delta_{\text{Chamber}} = \sqrt{\frac{2}{3} \left[ \frac{2}{\sigma_B^2 - \left( \frac{\Delta_{\text{MS}}}{2} \right)^2} \right]} \]

A similar calculation for \( \text{Diff}_A \) yields

\[ \Delta_{\text{Chamber}} = \sqrt{\frac{1}{6} \left[ \frac{2}{\sigma_A^2 - \Delta_{\text{MS}}^2} \right]} \]

Using 3 planes, the same chamber resolution assumptions and the three points (0,A), (1,B) and (2,C), again following Bevington, we find that three point line fits yield

\[ \text{Diff}_B = \frac{A - 2B + C}{3} \]

giving

\[ \sigma_B^2 = \frac{6}{9} \Delta^2 + \frac{1}{9} \Delta_{\text{MS}}^2 \]
leaving

\[ \Delta_{\text{Chamber}} = \sqrt{\frac{3}{2} \left[ \sigma_B^2 - \left( \frac{\Delta_{MS}}{3} \right)^2 \right]} \]

and

\[ \text{Diff}_A = \frac{2B-A-C}{6} \]

giving

\[ \sigma_A^2 = \frac{1}{6} \Delta^2 + \frac{1}{36} \Delta_{MS}^2 \]

leaving

\[ \Delta_{\text{Chamber}} = \sqrt{6 \left[ \sigma_A^2 - \left( \frac{\Delta_{MS}}{6} \right)^2 \right]} \]

Using these methods we can see that each of the eight difference spectra will have different widths, but can all be used in comparable ways to calculate the intrinsic chamber resolution and the multiple scattering contribution. It is also interesting to note that because the system is symmetric as far as reconstruction is concerned, the first and third chamber difference spectra will be identical.
4. Results and Conclusions

We analyzed data from the summer testing runs using the Q data acquisition and analysis system and the Laboratory for Nuclear Science Computer Facility. Example plots of the difference spectra from these runs, for both the three and two point fits, are shown in figures 16a, b, c and d. The Y-axis, of these plots are all in log format to illustrate the background. The background is not large enough to be a problem but it does have structure. We believe this is due to events that have an incorrect left-right decision, an incorrect wire assignment, or both.

The multiple scattering contribution can be calculated according to the following formula\(^8\) which gives one sigma, in radians, of scattering:

\[
\theta_{MS} = \frac{14.1\text{MeV}}{p\beta} \sqrt{\sum_{\text{All Materials}} \frac{L}{L_R}} \left[ 1 + \frac{1}{9} \log \left( \sum_{\text{All Materials}} \frac{L}{L_R} \right) \right]
\]

Making the approximations that the scattering occurs within 1/2 of the chamber separation on either side of the middle chamber, and that this averages out to the scattering being approximated as occurring at the second chamber itself we find the average scattering angle. Converting this to a scattering distance 12.7cm away (at chamber three), and making the further approximation that the scattering is gaussian, multiplying by 2.345 gives the FWHM of the scattering uncertainty\(^9\). Using the values in Table 3 we find that 250MeV electrons have a FWHM scattering uncertainty of 315 microns.

---


Figure 16a) Three point line fit difference spectrum, Y for plane 1

Figure 16b) Three point line fit, Y for plane 2

Figures 16) Difference Spectra for two and three point line fits in X and Y. These plots are in Log format.
Figure 16c) Two point line fit, Y for plane 1

Figure 16d) Two point line fit, Y for plane 2
Using a fitting routine, we found the FWHM of each of the difference spectra. Tables 4a and b list these values for high and low incident particle rates. The Bates laboratory uses a pulsed electron accelerator so the incident electrons come in bursts or "beambursts." We thus define our rate in terms of these beambursts: rate = triggers/beambursts, where triggers is the number of events that trigger a TDC start. The table further lists the reconstruction resolution which is determined by setting the multiple scattering contribution, Δms, equal to zero. Using all these methods the average intrinsic chamber position resolution for electrons is 174±9 microns, consistent with that reported by Atencio\textsuperscript{10}, and the trajectory reconstruction resolution is 216±7 microns. These results indicate that the intrinsic resolution of the chamber is not limited by high rates, as the resolution remains the same within experimental error.

<p>| | | |</p>
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<tr>
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Table 3) This table gives the calculation values and calculations for the multiple scattering contribution to the resolution. These values come from the *Review of Particle Properties*, Review of Modern Physics, or are calculated from LRgas = %gas·Chamber width.
<table>
<thead>
<tr>
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<th>FWHM of Difference Spectrum</th>
<th>Chamber Resolution</th>
<th>Reconstruction Resolution</th>
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<tr>
<td>3 Point ΔX1</td>
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<td>3 Point ΔY1</td>
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<td>3 Point ΔY2</td>
<td>173.2 Microns</td>
<td>169 Microns FWHM</td>
<td>212 Microns FWHM</td>
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<td>515.5 Microns</td>
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<td>2 Point ΔY1</td>
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<tr>
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Table 4a

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<td>214 Microns FWHM</td>
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<tr>
<td>3 Point ΔY2</td>
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<td>2 Point ΔX2</td>
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<tr>
<td>2 Point ΔY2</td>
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<td>175 Microns FWHM</td>
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<tr>
<td>Average</td>
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<td>173 Microns FWHM</td>
<td>215 Microns FWHM</td>
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<tr>
<td>STDEV</td>
<td></td>
<td>9 Microns FWHM</td>
<td>7 Microns FWHM</td>
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</table>

Table 4b

Table 4a and 4b show chamber and reconstruction calculations for high rate data (rate = 5.0 triggers/beamburst) and for low rate data (rate = 0.7 triggers/beamburst) respectively.
Additional analysis for proton trajectories has been done, but because of insufficient statistics, we cannot definitely say that the two resolutions are the same, but we can say they are of the same order.

Although there are many improvements to be made to the detection system of the OOPS, this research has shown that three major improvements will be of significant use. Firstly, we can reduce the multiple scattering effect by using helium instead of air around the detection system. Furthermore, the background in the difference spectrum is on the order of 10% and appears to be due to incorrect left-right or wire number determinations because there are peaks at interval and half interval wire spacings. After wire calibration and left-right decisions have been made, if we minimize the difference value for events that have a high $X^2$ reconstruction by trying different left-right and wire number combinations in software we may be able to make the correct decisions and get better resolution. Finally, a better alignment of the detector package can be made if a collimator that is exactly centered and has with a finer width in X and Y is used.

The HDCs have excellent resolution and are mechanically well aligned. The angular resolution of the spectrometer will be limited only by the multiple scattering, not the detector resolutions. This makes the detector system for the OOPS more than adequate for the needs of upcoming experiments.
References


Acknowledgements

I would like to thank Professor William Bertozzi, the Medium Energy group and the physics departments of both MIT and the University of Illinois for their involvement in this thesis.

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I would also like to thank my many friends who listened to me talk about this project and supported me in everything I did. Finally, I would like to thank my parents and family for the never ending love and support they gave during this time, as always.