Drift Chamber Fits and Tracking in the Triumf Weak Interaction Symmetry Test (TWIST)

by

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Abstract

A brief overview of the TWIST detector and experiment is given. The methods used to reproduce drift time spectra, drift time resolution dependence on distance from the hit wire, and multiple scattering effects for a GEANT3 Monte Carlo simulation of events in this detector are outlined, and the theoretical basis for these effects and approaches are examined. Observed effects and plausible values for some Monte Carlo parameters are introduced, as are possible difficulties. In particular, the shift in focus for the approach to multiple scattering from the whole detector correction to a piecewise correction is examined. Future approaches to the in depth completion of this project are suggested.

Contents

List of Figures

List of Figures

1 Overview of the TWIST Detector and Experiment, Introduction

The TWIST detector is a symmetric series of scintillators, proportional chambers, and drift chambers assorted to allow precise tracking of μ^+ and e^+ particles, encased in a recycled MRI magnet at the end of the M13 beamline at the Tri-University Meson Facility (TRIUMF) in Vancouver, British Columbia, Canada. Separating the two halves of the detector is a muon stopping target. Each drift chamber consists of wires oriented at 45° (u and v axes) to the horizontal and vertical (x and y) axes, in a volume of dimethylether (DME) gas. The medium between the chambers is helium gas. The μ^+ produced are decay products of the M13 beam π^+, and decay according to

$$\mu^+ \rightarrow e^+ + \nu \tag{1}$$

Because of the magnetic field, the e^+ follow a helical path defined by some initial angle and momentum, determinable from the track recorded by the chambers along with the known magnetic field strength. The angular and momentum distributions of several such decays may be used to measure the Michel parameters ρ, δ, ξ, and η. The goals of the experiment are to produce these measurements at precisions of 1 in 10^{-4}. This demands a clear understanding of the detector, which must be demonstrated in the Monte Carlo simulation and experiment analysis software (MOFIA). As such, drift time fitting techniques are currently being implemented into the Monte Carlo and analysis code. While many of the algorithms had been previously coded, determination of the details of their use and influence on the simulation and values of input parameters had not been investigated. The three effects recently examined were drift time spectra, drift time resolution, and multiple scattering.

2 DC Drift Time Fitting

2.1 Drift Time (TDC) Spectrum

2.1.1 Theory and Methods

The GEANT Monte Carlo package simulates a detector based on an assortment of volumes defined and positioned by the user. For example, in the

TWIST detector itself, the helium volume is defined with several daughter volumes of DME arranged throughout the length of the detector to represent the drift chambers. Within each drift chamber several thin cylindrical volumes are defined and positioned to represent the sense wires. For the purposes of determining drift time fits, each drift chamber is also separated into numerous symmetric cubical cells. The space-time relation (STR) callibration files produced by the GARFIELD software give the correspondence between drift time and position at numerous points within these cells. These are required as the equal drift time contours within a cell are roughly circular close to the hit wires, but become ellipses of significant eccentricity nearer the edge of a cell. At the edge of such a cell, the magnetic field becomes null (due to the symmetry between wires) and drift time becomes infinite.

The reconstruction of ion drift times within these cells in the Monte Carlo simulation requires the correct callibration of several interrelated effects to generate realistic circumstances. This may largely be done by reproducing distributions of various effects, one of the most important of these being the drift time itself. Originally, this fitting procedure was attempted using a histogram filled at all drift chambers for all hits on a given wire. It became apparent, however, that the travel time between chambers (time of flight) could cause difficulties in discerning the desired effects, as could the lapse between the first wire hit and later hits. The histograms were therefore redefined to only fill at a given plane (the ninth DC chamber) and a short loop was coded in order to output only the first hit on the wire (see Appendix D, Listing 1). This was not entirely straightforward, as drift times are not stored in chronological order by the Monte Carlo. Other problems that were dealt with were the removal of cutting out of tracks due to drift time information imposed by the analysis, and the removal of a sudden spike at time = 0, caused by the truncation method applied by the FORTRAN 77 function `IFIX` (replaced with the rounding function `NINT`).

Three parameters were available for the tuning of the spectrum, namely, a Gaussian smearing σ of the drift time (representing the inherent detector resolution), the mean spacing between ion clusters, and a linear shift parameter t_0, which gave a straightforward left or right shift of the entire spectrum. The expected effect of an increased cluster spacing was to increase the probability of a recorded hit far from the wire, whereas an infinitesimal cluster spacing would always require the particle's closest approach in time to be recorded. Initial trials utilized $120 MeV/c$ μ^+ as approximations to the comparison data ($120 MeV/c$ π^+) as pions were not at that time available in the

Monte Carlo. When pions were implemented properly into the code, they too were run as well as e^+, with the intent of examining the effect of particle type on the tuning of the parameters. Another effect briefly examined was particle momentum, in particular for positrons.

2.1.2 Results and Analysis

Plots of the various TDC spectra are shown in Appendix A. Figures 1 and 2 show the relative shifts of the leading edge and peaks of the spectrum for changes in the ion cluster spacing and DC resolution respectively. This is quantified in Table 1. As expected, a larger cluster spacing moves entries from the small drift time region towards the tail region. Also as expected, larger Gaussian smearing factors on the drift time cause the leading edge to spread to lower times and flatten the peak. This is easily understood given the implementation of this parameter: given an actual drift time t_{act},

$$t_{smeared} = t_{act} + \sigma G \tag{2}$$

where G is a random number distributed on a Gaussian. This also explains the seemingly impossible negative drift times output by the Monte Carlo (as G may be positive or negative). Such an effect only occurs in real data as a result of resolution in the electronics.

Plots are also shown of Monte Carlo against real data for three different particles: $120MeV/c$ μ^+, $120MeV/c$ π^+, and e^+ at momenta of $40MeV/c$ and $20MeV/c$. Reasonable fits were produced for all of these, though no detailed shifting was done, as the time resolution constraint had not yet been fulfilled. However, it is interesting to note that all four plots were achieved with a smearing factor of $2.5ns$, with various shifts in cluster spacing and time zero. Also important is the unexpectedly large change required in the cluster spacing to compensate for changing between e^+ and the other two particles. In addition to this, a change in particle energy causes a relatively small change in the TDC spectrum, also shown in a figure. It is uncertain at this point whether these effects are real or erroneous.

2.2 Drift Time Resolution

2.2.1 Theory and Methods

The Gaussian smearing of the drift time was one of the parameters utilized to reproduce appropriate TDC spectra. As noted, the resolution represents the inherent resolution of the detector DC's (and in some respects cannot be separated from the resolution in the electronics, as well). The determination of the correct value for this parameter was attempted using histograms of residuals between analysis drift distance and measured drift distance. How these values arise is described below, alongside the treatment of the Kalman filter. This offered an additional constraint on the tuning of the TDC spectrum (and vice versa), useful as it was uncertain whether or not there was more than one way to tune the three drift time parameters.

The space-time relation for the hit cells in the TWIST detectors is not linear, a consequence of the non-uniform nature of the electric field around the hit wire. As mentioned in the experiment overview, equal time contours (isochrones) in the cell are not the same shape as equal distance contours far from the wire, but rather become increasingly elliptical. An approximate relationship between space and time in the cell may be taken from the TDC spectrum, as

$$r\left(t_k\right) = \frac{r_{max}}{N_{tot}} \sum_{i=1}^{k} \Delta N\left(t_i\right) \tag{3}$$

where $r(t_k)$ is the radius at a given time, r_{max} is the maximum hit radius in the cell, $\Delta N(t_i)$ is the height of the ith bin of the TDC spectrum, and N is the total content of the TDC spectrum[1]. Given the TDC spectra examined earlier, this implies small changes in r at large times (few hits per bin) and large changes at small times, and conversely, greater uncertainty in distance near the wire than far from the wire.

Early on, several functional forms were attempted, including constant and linear, as well as those determined by a linear approximation to small changes in exponential Ae^{Cx} and seventh degree polynomial fits to the drift time versus distance histograms output by the analysis code. Later attempts utilized a piecewise function suggested by the examination of the effects of several constant values for the parameter. Data was analyzed by Gaussian fits to the drift time residual distributions. These histograms were defined at $100\mu m$ increments in distance from the hit wire. All such attempts were eventually abandoned for several weeks as the STR files were regenerated to fix an oscillating structure observed in the TDC spectrum's tail, however.

Following the fitting of the TDC spectra, and the subsequent obtaining of a probable drift time smearing value of $2.5ns$ that allowed a reasonable drift time spectrum for all particles given some change in the cluster spacing, the resolution question was returned to. In these later attempts, Gaussian fits were not used, as the wire volumes were removed due to erroneous effects in the simulation occurring after hard scatters off of the wires (whereby the π^+ being simulated entered the experimental volume (GEANT code `EVOL`) surrounding the detector and the GEANT step size became very small). This resulted in more than 60000 steps being computed, at which point the event was abandoned and no data was available for analysis. Ratio plots of Monte Carlo to data were instead examined.

2.2.2 Results and Analysis

The ratio plots produced after the TDC spectrum fitting are shown in Appendix B, Figures 7 to 28. These were produced with a 0° beam, as including any other angle gave rise to problems related to assumptions made by the track fitter, wherein the angle in the fit is underestimated. Because of the removal of the wires from the simulation, the large scattering tails are only evident in the real data plots. Similarly, the higher peak at zero close to the wire in the Monte Carlo likely resulted from the same effect (the tails being redistributed into this peak), though a correction of the GEANT code and subsequent runs with wires present is necessary to confirm this. Production of reasonable fits in this region is further frustrated by the large sensitivities present. For example, if distance is plotted as a function of time, it is increasing steeply at low times (the best exponential is too shallow in this region). Then a small error in the drift time fit can produce large residuals in distance close to the wire. Similarly, there are uncertainties in a Monte Carlo to Data comparison due to a threshold energy for registering of an ion cluster imposed on real data that is not implemented in the Monte Carlo. This affectsclusters generated in the region close to the wire, as unlike ion clusters far from the wire they do not generate an avalanche effect, increasing their visibility. Finally, any error in the cluster spacing could largely influence the this region, as it removes statistics from the first few bins and replaces them in later ones. It is seen that the comparison gradually becomes more reasonable, and is relatively decent in the range of $400\mu m$ to $2000\mu m$, the latter corresponding to half the edge length of the cell (the farthest hit registered by a 0° beam with infinitesimal cluster spacing). Hits beyond this region would have been a result of multiple scattering or cluster spacing (Figure 28), which is once again relatively uninterpretable. These plots were produced with a constant time smearing factor of $2.5ns$, the same factor used to produce the reasonable TDC spectrum fits earlier. Despite the implementation of a linear function in the Monte Carlo, such a constant parameter appears to be adequate, as simulations demonstrated very good fits at large times regardless of the smearing parameter itself. It is at these large times that a function linear in time would have an effect. While far from conclusive, this does provide some evidence that this may in fact be the correct value for this parameter, or is at least a probable starting point for the future studies into this effect.

The final figure in Appendix B (Figure 29) demonstrates the current difficulties encountered by the filter in the treatment of angled tracks. This effect must be dealt with prior to any verification of the drift resolution value.

3 Multiple Scattering Correction

3.1 Whole-Detector Scattering Estimation

3.1.1 Theory and Methods

Initial attempts to discern the multiple scattering contributions in the TWIST detector involved an estimation of the overall spread in xy position at each of the drift chamber foils, the same quantity measured by the chambers themselves. Such an approach was motivated by the belief that a set of two dimensional calibration files (one for each drift chamber) could be created by the study of expected dependences. Namely, one formula for the RMS multiple scattering in a Gaussian approximation may be given as

$$\sqrt{\langle\theta^2\rangle} = z\frac{20[MeV/c]}{p\beta}\sqrt{\frac{x}{L_{rad}}}\left(1+\frac{1}{9}log_{10}\frac{x}{L_{rad}}\right) rad, \tag{4}$$

where θ is the scattering angle, z is the charge of the incident particle, β is v/c of the incident particle, p is the momentum of the incident particle in MeV/c, x is the distance travelled through the scattering material, and L_{rad} is the radiation length of the medium, the distance through which the e^- energy is lowered by radiation loss by a factor of $1/e$ (e being the elementary charge)[2]. The parameter pair that would determine multiple scattering corrections would be initial particle momentum p_0 and the initial angle of this momentum with the z axis (perpendicular to the uv plane), denoted in this case θ (not to be confused with the scattering angle in the above equation). It is apparent from the equation that an increase in the initial angle (increase in the volume of DME travelled through) should increase scattering, as should a decrease in initial momentum. Tests of this were done with physics effects removed, with the obvious exception of scattering itself, so as to isolate the multiple scattering effects from other effects. Such involved defining the appropriate histograms directly in the simulation (as opposed to analysis) code (see Appendix D, Code Listing 2). The resulting plots were assumed to approximate Gaussians and fit as such using predefined `hbook` functions. This approach was utilized instead of RMS estimations, due to long tails on the distributions resulting from hard scattering off of DC wires which greatly influence the RMS values despite the small probability of their occurence. The Gaussian fits were not greatly affected by these tails in most cases.

Early simulations considered particles originating within the muon stopping target. It was later decided that this was, however, an incorrect way to determine the amount of multiple scattering in the detector, as uncertainty within the tracking due to scattering within the dc chambers is not correlated with the scattering in the target. Put another way, the scattering within the target causes the tracking of the DC hits to suggest an emerging anglular distribution at the edge of the target, which does not effect the tracking of the particle through the chambers themselves and must be examined separately to give the error in the decay angular distribution. As mentioned, a dependence examined was that of the initial particle momentum. As may be seen in (3), an increase in momentum and energy would decrease the multiple scattering effects. The extent of this effect in the Monte Carlo was examined over a large momentum range, from $20MeV/c$ to $60MeV/c$, and the resulting σ vs z curves plotted against each other. The θ dependence, which was to be included with the momentum in the scattering correction files, was similarly examined in the range 20° to 40°. The expected effect here was an increase in scattering with increasing angle, given the fact that increasing this angle, or, alternatively, increasing the xy momentum p_{xy} with respect to p_z, increases the volume of DME travelled through when a drift chamber is encountered. Such a path allows a larger maximum scattering angle and thereby demands a greater deviation in the Gaussian approximation. These effects were examined both with the simulated detector magnetic field off (straight tracks) and on (helical tracks). The helical tracks exhibited another expected complication in the scattering, a focusing of the beam caused by the magnetic field. This causes a smooth oscillation in the xy spread caused by the multiple scattering. The theoretical intuition for this effect results from the idea that if we allow a change in θ at a position (x_0, y_0, z_0) in the detector, the angle change will cause a change in the radius of the helical path of the scattered particle. However, given the periodic nature of the helix, it must reach a later point z along the axis of the detector at which its position in space is given as (x_0, y_0, z). Then diverging tracks must reconverge to some extent at some later position. This effect further motivated a study of the effect of changing the angle ϕ of p_x to p_y, with Gaussian fits as before and later by defining a new histogram of x against y for a given detector foil, to examine a dependence that was revealed but not understood (suggesting an error in the code or the use thereof, or the need to increase the number of scattering calibration parameters to three for each DC plane). Due to the eventual decision to alter the approach to multiple scattering correction to consideration of individual planes (described below), this effect was never investigated.

3.1.2 Results and Analysis

Several plots produced during the whole detector multiple scattering study are shown in Appendix C, illustrating several of the dependences described above. Only the first two figures (30 and 31) were produced with the particle origin inside the stopping target; the others put the source immediately after its boundary in the Monte Carlo. The effect of the target can be seen through a comparison of the $30MeV/c$, 20° curve (Figure 31, red) with the $\theta = 30°$, $\phi = 0°$ curve in Figure 3. Given the θ dependence suggested in the first two figures (an increased θ corresponds to increased scattering), it might be expected that the higher angle beam started outside the target would scatter more. The effect of the target overshadows this, however. At $z = 20cm$, the positrons originating within the target have a sacattering σ of $8mm$, whereas those originating outside have been scattered approximately half of that. This effect is lessened downstream. Also apparent in Figures 30 and 31 is the increased multiple scattering at lower momenta and higher angles. The oscillations are due to the magnetic focusing effect; their smooth shape is apparent in the dense stack hits near $z = 50cm$. No quantitative evaluation of these effects was attempted, because of the relatively dramatic ϕ dependence observed in Figure 33, which would have neccesitated a third (not understood) parameter to be included in calibration files if they were in fact created. Figure 32 was generated in response, revealing that any such effect is much less pronounced when the magnetic field is removed.

Figures 34 and 35 are two dimensional histograms of the xy hit spectrum for the entire thirtieth foil. Though low in statistics, these clearly show the bending and flattening of the scattered distribution (expected to be approximately a two dimensional Gaussian) into a circular ring for a large ϕ. No study of this effect was conducted, as attention shifted towards implementing the kinking method of multiple scattering correction.

3.2 Straight Track Kalman Filter Kinking

3.2.1 Theory and Methods

As noted, the above attempts to estimate multiple scattering throughout the entire TWIST detector neglected the need to incorporate uncertainty correlations resulting from the knowledge of previous scattering effects earlier in the detector. It was therefore decided to instead incorporate a technique whereby the multiple scattering is considered as a kink in the particle track at 'kink planes' positioned at each of the DC positions, and propagating the theoretical track as if some known change in θ had occured. This propagation then carries with it all previous information about earlier kinks in other chambers, eliminating the need for a mathematical treatment of the correlations in the analysis[1]. This is analogous to the concept of a Kalman Filter[2], a tool that had already been investigated and largely implemented in the TWIST analysis code, though the required kinking was not yet included.

The filter essentially uses several vectors of fit and measurement parameters along with transformations to determine the most probable overall track fit. More specific to TWIST, an event in the detector produces several measurements of position in the drift chambers, which the analysis is to fit with a linear or helical track. Such a measurement is denoted $\vec{x_m}$ and is a vector of three postion components u, v, and z and a time component t. The state vector $\vec{x_f}$ output by the filter corresponding to this measurement will have components of momentum p, angles θ and ϕ, radius r, and time t. A transformation H between these is defined so that

$$\vec{x_f} = H_m \vec{x_m} \tag{5}$$

and another matrix F_t is used to propogate the filter from the current filtered measurement to produce the next prediction. A weighting of the measure-

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[1] For more information on the kinking technique of tracking, see [3]

[2] The Kalman filter was originally described in a famous paper in 1960 by R.E. Kalman. For a more complete treatment, see [1]

ment against the prediction is achieved using yet another matrix K_f dependent on the covariance of the measurement and prediction; then the filtered state vector is given by the equation

$$\vec{x_f} = \vec{x_p} + K_f(\vec{x_m} - H_m\vec{x_p}) \tag{6}$$

The filter begins by determining an initial guess as to the value of $\vec{x_f}$ at the particle origin. After each step is filtered, a new set of parameters (and therefore a new propagation) is determined to continue the track on to the next plane. Iteration over all the drift chambers produces a piecewise function that may better account for uncertainties such as multiple scattering than a straightforward least squares fit. While the filtering process accounts for the lessened uncertainty in a later plane given the measurements in previous planes, it does not account for the fact that, prior to this fitting, information had been gathered about previous states of the particle. In other words, given that we have measured the particle position in three planes A, B, and C, we have gained a better estimate of where it was in B based on where it was in A, but because we also know where it ended up in C we can still do better. To complete this procedure, the filter reiterates back through the detector, beginning at the final plane, this time taking the vectors $\vec{x_f}$ as 'measurements' and outputting 'smoothed' vectors $\vec{x_s}$. This smoothing process allows the filter to use all the information gathered to produce the fit.

As noted, this was largely implemented, but still required the inclusion of multiple scattering kinks. In the case of straight tracks, a kink was allowed at each drift chamber, based on a parameter θ_{MS} added to the Kalman filter predicted measurement covariance matrix elements corresponding to p_x/p and p_y/P. It is given by the short code segment

```
! Add multiple scattering
      IF(BField == 0) THEN
         nextP%Cp(3,3) = nextP%Cp(3,3) + ((1+hitP%Xf(3,1)**2)*ThetaMS)**2
         nextP%Cp(4,4) = nextP%Cp(4,4) + ((1+hitP%Xf(4,1)**2)*ThetaMS)**2
      ELSE
         ! not implemented for helices
      ENDIF
```

Histograms of the residuals output by the Kalman filter (differences between smoothed and measured results) were produced and examined. It was assumed that the correct value for θ_{MS} would produce constant residuals throughout the detector. In other words, it would not be so high as to force the measured value to be taken as correct downstream the detector (infinitesimal residuals), nor would it be so low that the propagated position would be chosen in this region (maximal residuals). A possible value for this mean scattering angle was eventually computed in the GEANT simulation by sending e^+ through a single pair of drift chambers (a UV-module), measuring the incident and emerging angles and histogramming the difference.

3.2.2 Results and Analysis

Plots of the effect of the magnitude of θ_{MS} (Figure 36) as well as the GEANT computation of this parameter (Figure 37) are shown at the end of Appendix C. Currently, determination of the value of θ_{MS} are needed, requiring a more precise determination of detector resolution and a stronger understanding of the Kalman filter. However, the expected effect of changing its value may be observed, whereby a large θ_{MS} gives the filter total freedom to choose the measured value over the predicted value, whereas a small value weights the predicted value much more strongly. It seems apparent that this technique is workable, once the other difficulties are solved.

4 Summary, Conclusions

At this point, decent drift time fits and probable drift chamber resolution comparisons have been achieved, though not in any great detail and with some verification, for example, using clean, unmodified code. The use of a single drift time resolution parameter ($2.5ns$) to produce these fits is an proposed, but must be confirmed, primarily with wires implemented in the Monte Carlo and in light of the unexpected particle type and momentum contributions to the TDC spectrum ion clustering requirement. The effect of particle type in particular must be investigated to verify what has been obseved. The qualitative effects, however, caused by changing the TDC parameters have been reproduced repeatedly with several versions of the code. These may be useful in later adjustments to the TDC spectrum.

Work is still required on fitting the drift time resolution histograms. However, this can only be attempted with an improved understanding of the Kalman filter. The $2.5ns$ value will likely be a good starting point for when this effect is reexamined. At this point there seems to be some agreement between the TDC spectrum and residuals histograms that this value may be near to optimal.

The implementation of a kinking method of multiple scattering treatment seems to be advantageous, although issues in the Kalman filter's treatment of the fit must be addressed. Although the overall trend caused by the θ_{MS} parameter has been confirmed, the optimal value for the parameter has not. Furthermore, it may be helpful to understand the whole detector multiple scattering effects observed at least at an intuitive level, namely, the smearing of the xy distribution into a ring instead of a spot. Following a verification of the implementation of the straight track kinking, examination of the plane alignments suggested by the analysis would be instructive to check for any improvement.

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