Chapter 5: Tests Of The Forward Muon Reconstruction Code

In order to test the performance of the MTREC code, the H1SIM program was used to generate a dataset with 1,000 μ^+ and 1,000 μ^- (one track per event) with each of the following momenta: 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 175, 200, 225 and 250 GeV. The muons were generated in the range $-180° < \phi < 180°$ and $4° < \theta < 17°$, covering the whole of the forward muon system.

The muons were tracked from the H1 vertex straight to the forward muon system with the rest of the detector not present so that the parameters of the muons were well known at the start of the forward muon system and the muon tracks produced were radial. The simulated dataset was processed by the MTREC module with an option to produce histograms and n-tuples of the data switched on. The data were then analysed using the LOOK program. It should be emphasised that this is the cleanest possible environment for running MTREC and the results presented here are the upper limits of the code performance, not the expected values when the code is run on real data.

Previous studies [50] on the performance of the reconstruction code used an older version of the MTREC code which did not preserve full covariance information throughout and in which certain approximations were made, valid at the time as the phi chambers had not been installed. Newer versions of the code (H1REC version 3.09 and above) contain exact evaluations of co-ordinate transformations including full covariance information. In order to fully assess the performance of the reconstruction, studies were made using the new code with theta layers only and with phi layers installed. Only one simulation was performed but the phi chamber hits were ignored in one run of the reconstruction.

Momentum Resolution

The momentum resolution of the forward muon system is driven by two factors: multiple scattering in the toroid and the position resolution of the chambers. Both of these lead to errors in measuring the amount of bending suffered by the particle in the toroid. The amount of bending in the toroid is given by

$$\delta\theta = \frac{0.003\ B\ \delta l}{p}$$

as before, where B is the field in Tesla, p is the momentum in GeV/c and δl is the distance travelled in the field in cm. The scatter about this mean deviation due to multiple scattering in the iron toroid also varies as $1/p$. Hence, the fractional error on p, $\sigma(p)/p$, is

$$\frac{\sigma(p)}{p} = \frac{\theta_0}{\delta\theta}$$

where θ_0 is the deviation due to multiple scattering as before and the momentum dependence cancels. Taking notional values of B=1.5 T and δl=120 cm gives the total bending in the toroid as $0.576/p$ radian GeV. The value of θ_0 computed for the whole toroid is $0.140/p$ radian GeV. The resolution expected by considering just multiple scattering is therefore $\sigma(p)/p \approx 24\%$.

The resolution of the chambers contributes to the momentum resolution by producing an error on the measured theta angle of the segments before and after the toroid. As this error should be independent of momentum and the bending depends upon $1/p$, this contribution is expected to rise linearly with p.

The order of magnitude of this error may be estimated by assuming that the error in the radial distance from the beamline for a given hit is 250 μm (only true when the segment is in the middle of an octant). Considering only the first and last hits, the spacing between the hits is 65 cm and error on the slope of the line defined by these two hits is $\approx 5 \times 10^{-4}$. Since there are two segments involved, the error in theta angles used to determine momentum comes to $\approx 8 \times 10^{-4}$ radians. Thus the resolution in position gives a contribution to the momentum resolution of order

of $8 \times 10^{-4}\ p/0.576 \approx 0.13\ p$ %/GeV. This contribution is only 0.7% at 5 GeV, so at low momentum the resolution is driven by multiple scattering. However, as segments are made using between three and six hits, the actual error on the theta angle is expected to be smaller than the above estimate.

The momentum resolution of the reconstruction code may be determined by comparing the reconstructed value of momentum with the value that was generated. Plots were made of $(1/p)_{MC} - (1/p)_{REC}$ where the subscript MC indicates the true value from Monte Carlo and REC indicates the value returned by MTREC. The plots were made in $1/p$ rather than p as the errors are approximately Gaussian in $1/p$ (at least at lower values of momentum). Initially, a Gaussian was fitted to each plot. However, above 100 GeV, the method of fitting used no longer converged, a Gaussian being a very poor fit to the distribution. The LOOK peak-fitter program [38] was then allowed to choose the form of the peak and the sigma and central value of this fitted peak were then used in the analysis of these higher momenta tracks. A constant error of 2×10^{-3} was assumed on the values from the peak fitter.

The sigma value of each peak then gives the momentum resolution at several values of p for both positive and negative muons. Figure 5.1 shows $\sigma(1/p)/(1/p)$, the value of $\sigma(1/p)$ from the fit divided by $1/p$ to give the fractional error. A straight-line fit to the resolution in figure 5.1(a) (without the phi chambers) gave a constant term of 22.3±0.4% and a slope of 0.057±0.005%/GeV. When the phi chambers were included, as in figure 5.1(c), the constant term became 23.4±0.3% and the slope was 0.049±0.004%/GeV. These values are consistent with the estimates calculated above. The resolution for radial tracks was not found to improve when phi chambers were included. However, the same is not expected to be true for non-radial tracks where the phi angle of the track, Φ, is no longer the same as the phi co-ordinate of the track, ϕ.

Figure 5.1: Fractional resolution in $1/p$ as a function of momentum for a) μ^+ without phi chambers, b) μ^- without phi chambers, c) μ^+ with phi chambers and d) μ^- with phi chambers.

In addition to the resolution, the value of momentum reconstructed must be checked for any systematic variation. A plot was made of the deviation of the centre of the peak in the $(1/p)_{MC} - (1/p)_{REC}$ plots, $\Delta(1/p)$, as a fraction of $1/p_{MC}$ against $1/p_{MC}$. This is shown in figure 5.2. It was observed that there was a systematic deviation: the magnitude of the reconstructed momentum was systematically too low at low momenta and too high at high momenta. The effect was found to be in the same sense for positive and negative muons. The effect was most pronounced at low values of momentum where the shift was as high as 10%. This effect is obviously not desirable and is not fully understood. It is possible that fitting a quadratic to the χ^2 distribution might introduce such a shift if the real χ^2 distribution were asymmetric.

Figure 5.2: Fractional systematic deviation in 1/*p* as a function of momentum for a) μ^+ without phi chambers, b) μ^- without phi chambers, c) μ^+ with phi chambers and d) μ^- with phi chambers.

A check must also be made to ensure that the error on the momentum as calculated by the reconstruction code is approximately correct. A residual plot was therefore produced. The value of the residual is given by

$$Residual = \frac{p_{MC} - p_{REC}}{\sigma_{REC}}$$

where σ_{REC} is the error on the momentum as estimated by MTREC. If the reconstruction is functioning perfectly, this distribution is a Gaussian centred at zero with unit sigma. If the value of the reconstructed momentum is wrong, the peak is shifted from zero. If the error estimate is wrong, the peak has sigma not equal to unity.

The momentum residual plots are shown in figure 5.3 with peaks from the LOOK peak-fitter superimposed. The peaks were found to be non-Gaussian and asymmetric. This may be a result of the fact that the distribution is Gaussian in 1/p rather than in p. Also, as the reconstructed value of momentum was found to have a systematic shift, it is possible that

summing over all values of momentum distorts the peak shape. The peaks were also found to be offset from zero, the net result of the systematic shifts measured above. However, their sigma values were close to 1.0, meaning that the error calculated by the reconstruction code was approximately equal to the spread of the reconstructed values about the true value.

Figure 5.3: Momentum residual plots for a) μ^+ without phi chambers, b) μ^- without phi chambers, c) μ^+ with phi chambers and d) μ^- with phi chambers.

Efficiency

The second major test of the reconstruction code is to evaluate how efficient it is at reconstructing muon tracks. The datasets generated were clean, with only one track per event, no noise added and no extra material in front of the chambers to produce showers or scatter the muons. The efficiency of the reconstruction code under these circumstances sets the upper limit for performance on data (which is certainly not clean in the above sense). The efficiency for reconstruction in a given bin is defined here as the fraction of tracks simulated within that bin that gave at least one track as an output. No requirement was made on the parameters of the output track.

Figure 5.4 shows the reconstruction efficiency for μ^+, μ^- with and without the phi chambers as a function of incoming track momentum, integrated over all incoming θ, Φ. The efficiency was found to vary from 80% for μ^+ (85% for μ^-) and rose to a plateau at 89±1%. The lower efficiency at low momenta is due to multiple scattering or a single large-angle scatter deviating a muon that passes through the edge of the toroid so that the muon leaves the toroid at its inner or outer radius, missing the later chambers. Negative muons are focussed in the toroid so those nearer the inner radius are more likely to escape than positive muons. The opposite is true at the outer radius, but the toroid inner radius is 65 cm c.f. the chamber inner radius of 48 cm whereas the toroid outer radius is 290 cm c.f. the chamber outer radius of 198 cm for theta layer one. The effect is therefore more important for the negative muons.

Figure 5.4: Reconstruction efficiency versus momentum for a) μ^+ without phi chambers, b) μ^- without phi chambers, c) μ^+ with phi chambers and d) μ^- with phi chambers.

Figure 5.5 shows the reconstruction efficiency as a function of incoming track θ, integrated over all momentum, charge and Φ. The drop-off which was observed below 0.1 radians and above 0.27 radians was due to the edges of the geometric acceptance of the chambers. The plateau was at 92.0±0.8%. The errors were based on the statistics in each bin. An efficiency of more than 100% may arise as the original dataset was generated with the events randomly spread over the full range rather than in discrete bins as for the momentum. The statistical fluctuations of the two figures are 100% correlated as the same input dataset was used for runs with and without the phi chambers. The inclusion of the phi chambers had no significant effect on the efficiency as a function of θ.

Figure 5.5: Reconstruction efficiencies versus θ a) without phi chambers and b) with phi chambers.

Figure 5.6 shows the reconstruction efficiency as a function of position within an octant, i.e. as a function of $\phi_{off} = \Phi - \phi_{centre}$, where ϕ_{centre} is the phi co-ordinate of the centre of the octant containing the track. The data were integrated over all momentum, charge and θ. There is no reason to expect that one octant be different from another in the simulation, so plotting against

ϕ_{off} gives eight times the statistics and hence allows smaller bins sizes. The plateau was at 88±0.7%. The drop-off observed in the first and last bins was due to the edges of the acceptance within an individual octant. The inclusion of the phi chambers was found to have no effect on the efficiency with Φ.

Figure 5.6: Reconstruction efficiencies versus $\phi_{off} = \Phi - \phi_{centre}$ a) without phi chambers and b) with phi chambers.

Resolution In Theta, Phi And Position

The momentum resolution of the forward muon detector is important for stand-alone measurements. However, muons in the forward muon system may also leave tracks in the forward tracker or the instrumented iron. In order to be able to link these tracks together it is necessary to know the resolution in the two track angles θ and Φ and the resolution in position, H1 *x* and *y*. It is also important to know the estimated errors on these measurements. The error estimated by the reconstruction code was checked using residual plots as was done for the momentum. The residual in a quantity *x* is defined as

$$Residual(x) = \frac{x_{MC} - x_{REC}}{\sigma_{REC}}$$

where x_{MC} is the true value of x from the Monte Carlo program, x_{REC} is the value of x returned by the reconstruction program and σ_{REC} is the estimate of the error on x returned by the reconstruction program.

Figures 5.7(a) and 5.7(b) show θ_{MC} - θ_{REC} for all tracks with and without the phi chambers present. As can be seen from the plot, the resolution was not well described by a Gaussian and the peak was therefore fitted using the LOOK peak fitter. The sigma of the peak without the phi chambers was 0.00161 radians and its centre was at $9x10^{-5}$ radians, consistent with zero. However, there appeared to be two contributions to the peak, one a sharp peak and one a much broader peak. This may be understood by considering the fact that the theta angle measured at the centre of an octant depends only upon the drift co-ordinate whereas at the edge of an octant it depends upon a mixture of the drift and charge division co-ordinates. The sigma of the peak with the phi chambers was 0.00111 radians and its centre was at $9x10^{-5}$ radians. The two component structure was much less pronounced. Figures 5.7(c) and 5.7(d) show the residuals in θ. The sigma values of the peaks were found to be 0.79 and 0.95 without and with the phi chambers respectively, suggesting that the error in theta was somewhat overestimated.

Figures 5.8(a) and 5.8(b) show Φ_{MC} - Φ_{REC} for all tracks with and without the phi chambers present. The sigma of the peak without the phi chambers was 0.266 radians and the centre was at 0.008 radians. The sigma of the peak with the phi chambers was 0.0027 radians and the centre was at 0.05. It was therefore concluded that the addition of the phi chambers allowed a much better measurement of the track Φ angle. Figures 5.8(c) and 5.8(d) show the residuals in Φ. The sigma values of the peaks were 0.84 and 0.94 without and with the phi chambers. This suggested that the errors were slightly overestimated by MTREC.

Figure 5.7: a) Resolution in θ without phi chambers, b) resolution in θ with phi chambers, c) residuals in θ without phi chambers and d) residuals in θ with phi chambers.

Figure 5.8: a) Resolution in Φ without phi chambers, b) resolution in Φ with phi chambers, c) residuals in Φ without phi chambers and d) residuals in Φ with phi chambers.

Figures 5.9(a), 5.9(b), 5.10(a) and 5.10(b) show x_{MC} - x_{REC} and y_{MC} - y_{REC} for all tracks with and without the phi chambers present. The sigma of the peaks without the phi chambers present were 1.0/1.0 cm for *x*/*y*, and the centres were found to be at 0.01/-0.04 cm. With the phi chambers included, this became sigma 0.172/0.166 cm and centre -0.005/-0.005 cm. It was concluded therefore that the overall precision of *x* and *y* measurement was improved by the addition of the phi chambers because good measurements were being made in two perpendicular co-ordinates rather than one good and one poor measurement. Figures 5.9(c), 5.9(d), 5.10(c) and 5.10(d) show the residuals in *x* and *y*, with sigma consistent with 1.0 for all plots.

Figure 5.9: a) Resolution in *x* without phi chambers, b) resolution in *x* with phi chambers, c) residuals in *x* without phi chambers and d) residuals in *x* with phi chambers.

Figure 5.10: a) Resolution in *y* without phi chambers, b) resolution in *y* with phi chambers, c) residuals in *y* without phi chambers and d) residuals in *y* with phi chambers.

The above resolutions were an average over the whole detector for a large number of tracks. There are systematic effects in these resolutions, particularly when the phi chambers are excluded. For example, measurement of the θ angle is dependent upon a good measurement of the radial co-ordinate. In the centre of an octant, this is the drift co-ordinate and hence is well measured. At the edge of an octant, this is a mixture of drift and charge division co-ordinates, giving a larger error on the measurement. Figure 5.11 demonstrates this, plotting the value of $\theta_{MC} - \theta_{REC}$ against $\phi_{off} = \Phi - \phi_{centre}$. The value of θ was reconstructed much better at the centre of an octant than at the edge when the phi chambers were absent. When they were present the difference in reconstruction across on octant was observed to be much smaller.

Figure 5.11: θ_{MC} - θ_{REC} against $\phi_{off} = \Phi - \phi_{centre}$ a) without phi chambers and b) with phi chambers, showing the systematic variation in θ resolution across an octant.

Real Data

The studies presented in this report have used simulated data generated by the H1SIM program with an error on the drift co-ordinate of 250 μm and an error on the charge division co-ordinate of 3.33% of the struck wire length. The chambers were assumed to be perfectly aligned and no noise hits were introduced. It has already been reported that the resolution on the drift co-ordinate for the real detector was 310±5 μm in 1992 and it is clear that much more work is necessary to align and calibrate the chambers so that the design resolution of 250 μm can be attained.

Studies are being carried out intensively at DESY, Manchester and Birmingham to understand the real data and to align and calibrate the detector. As yet, the low luminosity delivered by the HERA machine has meant that the main source of muons for the forward muon system has been beam halo. Of the particles created in such interactions, only muons are capable of penetrating the shielding around H1 in significant numbers and giving tracks in the forward

muon spectrometer. Figure 5.12 shows a beam halo muon track passing through the detector with the reconstructed track extrapolated through the toroid and the two segments used in forming the track superimposed. Figure 5.13 shows a heavy flavour event in the H1 detector where one of the two muons produced was reconstructed in the forward muon spectrometer.

Figure 5.12: A beam halo muon in the H1 forward muon spectrometer. Solid lines are the segments used in forming the track and the dotted line shows the extrapolation through the toroid at minimum χ^2.

Figure 5.13: A heavy-flavour physics event in which one of the two muons produced was detected in the forward muon spectrometer.