APPENDIX F

ALIGNMENT CONSIDERATIONS

F.1 General Remarks

The solenoid will be mounted in the warm bore of the CC cryostat and its final position fixed using fiducial marks placed on the outer vacuum jacket of the magnet cryostat which predict the location of the coil inside after it is cooled and energized. In general it is possible to measure the locations of such fiducials to 0.25 mm (0.010 in) or so in x and y, and perhaps z as well, in some coordinate system that can be referred to the remainder of the detector and ultimately to the colliding beams (e.g. a system based on the detector center beam).

By specifying that the total radial uncertainty in the location of the coil inside the cryostat does not exceed $\pm 5mm$, then the angular uncertainty in the direction of the field axis does not exceed $\alpha \approx 2 \times 5mm/2.56m = 4$ mrad. The survey tolerances (0.25 mm) do not appreciably increase this when the field is referenced to the TeVatron.

In order that the initial misalignment not significantly degrade over time (due to thermal or magnetic cycling) we specify that the magnet cold mass support system locate the coil reproducibly to e.g. twice the initial placement accuracy, $\pm$ 0.5 mm, so that the total misalignment never exceed $\pm$ 5 mm.

The silicon microstrip and scintillator fiber tracking systems will be mounted in the bore of the magnet and aligned to it so that the axes of the trackers and the magnetic field are parallel to the same tolerances. Thus the maximum misalignment between the axis of the field and the axis of these trackers will also not exceed ≈ 4 mrad.

In what follows we show that this tolerance is sufficient to preserve necessary alignment of the magnet both for machine requirements and for tracking requirements.

If it is determined that the field of the magnet is not sufficiently accurately known from the manufacturer's specifications, then the field can be mapped to find the field axis with respect to fiducial marks on the cryostat. In this eventuality, the final angular misalignment between the magnetic field and the TeVatron or the tracking system can be reduced to a fraction of 4 mrad.

F.2 TeVatron Requirements

It is necessary that the solenoid not generate closed orbit distortions in excess of 1.0×10^{-3} m (G. Goderre, FNAL AD, private communication) in the arcs of the machine after the stored beams leave the interaction point. While a fringing solenoidal field concentric with the beam and parallel to it cannot cause beam steering, one rotated by an angle α about any axis perpendicular to the beam can. If the magnet is in fact misaligned by such an angle α the integral

$$\int B dl = \int B_t tan\alpha dl = \delta B_s Z$$

is nonzero along the beam path, and this integral generates a net steering force on the beam. Here we write B_s for the average of the field $B_t tan\alpha$ over the magnet length, and Z the length over which this average filed is effective. Note that if the magnet is aligned to the beam so that α is zero, the beam need not even be precisely concentric with the field since the resulting field integral remains zero as long as the field at one end is symmetric with the field at the other.

The closed orbit distortion amplitude of the stored beam at point k generated by a non-zero "error field" integral $\delta B_s Z$ at the interaction point IP is given by

$$\Delta y = \frac{\sqrt{\beta_{IP}\beta_k}}{2}\frac{\delta B_s Z}{B_\theta \rho}$$

where β_{IP} is the beta function at the interaction point, β_k the beta function at point k, and B_θ is the beam guide field strength and ρ the machine radius.

Since for a beam particle of momentum p the guide field obeys $p = 0.3 B_\theta \rho$, we have at injection, $B_\theta \rho = 150/.3 = 500 Tm$ and at flattop, $B_\theta \rho = 900/.3 = 3000 Tm$.

At the interaction point, $\beta = 2m$, and in the arcs $\beta = 100m$. The condition that the closed orbit distortions not exceed $1.0 \times 10^{-3}m$ then implies that the "error field" integral obey

$$\delta B_s Z < \frac{2 \times 10^{-3} B_\theta \rho}{\sqrt{2 \times 100}}.$$

Now $B\rho$ is smallest at injection, so we find we must have for this most severe case

$$\delta B_s Z < 0.0707\, Tm.$$

We approximate the actual "error field" integral for the solenoid misaligned by an angle α as a 2 Tesla field effective over the physical length of the coil, 2.56 m,

$$\delta B_s Z = \int B dl \approx 2.0T \times 2.56m \times tan\alpha.$$

Then we have

$$tan\alpha < \frac{0.0707}{5.12} = 0.0138,$$

so

$$\alpha < 14 mrad.$$

Note that during collisions β_{rp} is smaller by a factor of about eight and the guide field term is larger by a factor of six so that during collisions the condition is easily met.

The support system of the magnet must maintain the rotational alignment of the magnet to the tolerance obtained in order to be useful at the TeVatron. For safety, we choose a specification that guarantees the misalignment to be substantially less.

F.3 Tracking System Requirements

Because a direct measurement of $p_\perp$ is provided by the tracking system and the magnetic field of the solenoid, is it necessary to examine how residual small relative misalignments between the trackers and the magnetic field will affect the accuracy of this measurement.

(It is noted that the tracking system is likely to participate in part of the **Level** 1.5 trigger so it will ultimately be necessary to consider how misalignment of this system can bias such a trigger. For example, if the tracking system is part of a $p_\perp$ threshold estimation for the trigger, then if it is displaced laterally a $cos\phi$ - dependance on the trigger threshold would result. Additionally if the tracking system is to be used to obtain track stubs or segments for the trigger, then the effect of misalignments of the field on this trigger must be examined. Such trigger-dependent topics are not considered in the following. They may well generate constraints that are more severe than those discussed herein).

Studies have been made of the resolution in $p_\perp$ promised by the full upgrade silicon and scintillation-fiber tracker systems. The results are eta-dependent and have been estimated for event vertices at $z = 0$ and for $z > 30$ (see **Figure F.3**).

The error in $p_\perp$ increases with eta and is larger for $z > 30$, but to key on the most stringent needs, we quote the result for eta $= 0$ and $z = 0$:

$$\frac{dp_\perp}{p_\perp} = 0.016 \oplus 0.002p_\perp,$$

where the first term describes multiple scattering and the second is due to measurement errors. Perfect knowledge of a perfectly aligned uniform field was used to develop this result, and no pattern recognition confusion was included. The undulations in the curves stem from the transitions in coverage between the ends of the tracker barrels and the discs at the specific values of eta involved.

For a particle with e.g. $p_\perp = 1$ Gev/c, roughly the lower limit desired in **DØ Upgrade**, the "geometry" term is 2×10^{-3}.

For a particle moving in a magnetic field we have,

$$p_\perp = \frac{0.3 \times B_z}{K}$$

where $\mathbf{K}$ = curvature = 1/R. Then

$$\frac{\sigma^2(p\_)}{p\_{}^2} = \frac{\sigma^2(B_r)}{B_r^2} + \frac{\sigma^2(K)}{K^2}$$

describes how the measurement uncertainties contribute to $\sigma(p\_)$ if the uncertainties in the knowledge of the values of the field are allowed to contribute. It is reasonable to require that these additional uncertainties not exceed 10% of those from the determination of the curvature, i.e.,

$$\frac{\sigma(B_r)}{B_r} \leq 2 \times 10^{-4}$$

at 1 Gev/c.

If the DØ upgrade tracking system is misaligned with respect to the field by a small angle α, then an uncertainty in the value for B_r is generated:

$$\begin{aligned} B_r^{actual} &= B_r^{nominal} cos(\alpha) \\ &\cong B_r^{nominal}[1. - \alpha^2/2]. \end{aligned}$$

Now if

$$\begin{aligned} \Delta B_r &= B_r^{actual} - B_r^{nominal}, then \\ \Delta B_r &= \frac{-\alpha^2 B_r^{nominal}}{2}, or \\ \frac{\Delta Bz}{B_r} &= \frac{-\alpha^2}{2}. \end{aligned}$$

For $\alpha = 4$ mrad,

$$\frac{\Delta B_r}{B_r} = 8 \times 10^{-6}.$$

This remains comfortably smaller than the limit specified above.

F.4 Vertex Resolution Due to Misalignment

Misalignment of the tracking system with respect to the magnetic field can also introduce errors in the determination of the z of a secondary interaction vertex.

If the tracking system is perfectly aligned to the magnetic field then B_r and B_ϕ are nominally zero. However, if the magnet axis is misaligned by an angle α then B_r and B_ϕ are

$\simeq B_r \times \alpha$. These uncertainties, while they do not contribute directly to the measurement of $p_\perp$ for any track, do contribute to the uncertainty of the location of the z of e.g. a secondary vertex.

Crudely, if a straight line is fit to a trajectory $p_\|$ which is actually curving due to a field $B_\perp = B_r \times \alpha$, then an angular uncertainty in the trajectory of the track is introduced that can be characterized by the total angle of bend of the track at its midpoint.

The curvature is not large: for even a $p_\| = 1$ Gev/c track, $R = p/(0.3 \times B_\perp = 1/0.3 \times 2 \times 4 \times 10^{-3} = 417$ meters. Taking the radial dimension $S \sim 0.15m$ of the silicon tracker as the characteristic length, then

$$\delta\theta = 0.3 \times B_\perp \times S/p_\|, or$$

$$\delta\theta = 1.8x10^{-4}.$$

Such an angular mismeasurement would contribute an error at the vertex of $\Delta Z = R \times \Delta\theta = 2.7x10^{-5} = 27$ microns. The resolution of the tracker, for e.g. $B \rightarrow \Psi \rightarrow \mu\mu$, calculated without this effect, has been given [1] as $\sigma_z = 220$ microns. Evidently the field misalignment $\alpha = 4$ mrad will not significantly spoil this resolution.

We conclude that if the magnet is constructed to readily-achieved engineering tolerances then the tracker systems can be installed into it and aligned to fiducials on it using standard optical survey techniques. The contribution to uncertainties in the measurements of particle $p_\perp$, or to the z coordinate of secondary vertices from errors arising from this process are entirely negligible.

Indeed, as was with the case for the CDF solenoid[2], even if the misalignment angle has been determined quite precisely by a field-mapping exercise it can be entirely ignored.

By an alternate viewpoint, nonuniformities in B_r stemming from the design of the magnet itself exceed a few parts in one hundred for extreme trajectories in the tracker, so the additional nonuniformity as estimated in the foregoing due to a small misalignment of the magnet axis is entirely negligible.

References

[1] **DØ** Note 1733, **E823 DØ** Upgrade, May 1993

[2] C. Newman-Holmes, *et al.*, "Measurement of the Magnetic Field of the CDF Magnet", Nuclear Instruments and Methods in Physics Research, **A274**, 1989, pp 443-451.

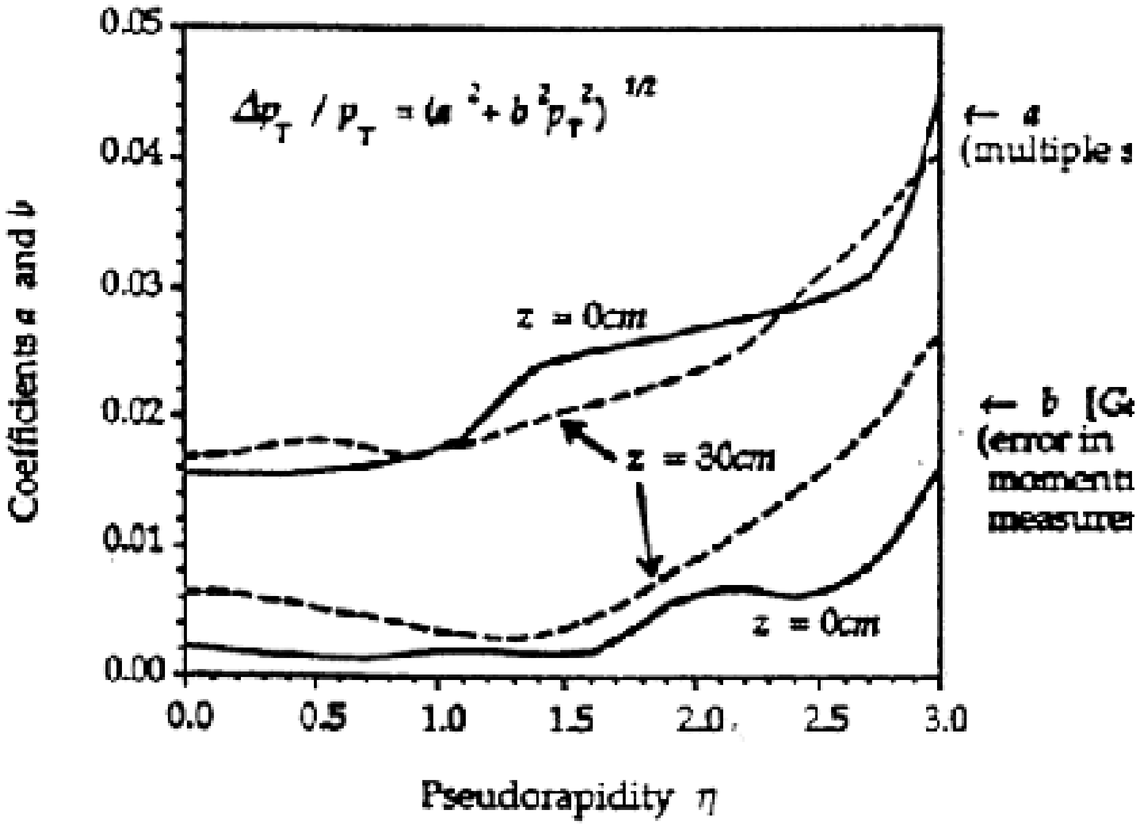

Figure F.1 Resolution of the DØ Upgrade Tracker