Alignment Requirements for the Muon Tracker

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Abstract

The alignment requirements of the muon arm are considered. An error budget is determined based on expected manufacturing tolerances, and expected alignment tolerances. Simulation results are used as a guide.

1 Introduction

The alignment tolerances for the muon tracker are very stringent since Monte Carlo simulations indicate that chamber resolutions approaching 100 microns are required to get the good mass resolutions of the vector mesons. The alignment of the muon system can be conveniently divided into two aspects, internal alignment tolerances of the chambers in the muon arm (local coordinate system (LCS)), and global alignment tolerances of the muon arm (global coordinate system(GCS)) with respect to the rest of the PHENIX detector. The internal alignment tolerances are the most stringent and will require very careful attention to the mechanical construction of the chambers at each station and the overall stability of the structural space frame holding the stations in the lamp shade magnet. This note will address the alignment requirements of the entire muon system so as to provide input to the mechanical design and assembly procedures of the chambers and the design of the space frame as well as providing the input required for the design of the active alignment system. Gravity, thermal, and magnetic motions of the muon arm are considered as static one time displacements that can be measured with optical and active alignment methods to the accuracys discussed below and therefore will not be mentioned. The only requirement is that the motions are within the range of the active alignment systems. The local alignment system (LCS) will be considered as the interior of the lampshade magnet with appropriate alignment fiducials. The details have not been worked out. However, in the following discussion the reference points will be the interior alignment fiducials.

2 Internal Alignment

The alignment requirements of the muon tracker involve specifications on the initial placement of the muon chambers in the magnet, the stability of the chamber systems after initial placement, the internal mechanical assembly of the planes in the station, the station to station alignment tolerance, and the alignment of the muon arm with respect to the rest of the PHENIX detector. Physics requirements will drive the alignment tolerances but practical considerations will define what is actually achievable. For this analysis the results of physics simulations will be used as the primary guide.

The relevant coordinate system for the muon arm is r, ϕ, and z since the Muon Arm is intended to measure the following characteristics of the detected particle,

p_t	transverse momentum by measuring the bend in the ϕ as a function of z;
θ	polar angle by measuring the radial coordinate, r, as a function of z;
ϕ	azimuthal angle.

However, the specifications of the LCS will generally be given in terms of the chamber measurement parameters, position along the anode wires (high resolution and approximately ϕ) and anode wire position (coarse resolution and approximately r). The Monte Carlo simulations take these parameters as the input and determine the expected performance of the muon arm for various physics parameters, i.e., mass resolution of the upsilon. A position resolution along the anode wires of 100 microns is desired. This corresponds to all contributions including the intrinsic chamber resolution and all mechanical construction and alignment uncertainties. Position resolutions in r of 0.5 cm and in z of 1mm are needed. The contributions to the resolutions in either r or ϕ can be tabulated as follows.

σ_{int}	intrinsic chamber resolution
σ_{mech}	accuracy for mechanical assembly of the individual planes.
σ_{align}	alignment accuracy from station to station
σ_{stab}	stability of each station
σ_{place}	initial placement accuracy of the octants

The Monte Carlo position resolution, σ_{mc}, is then

$$\frac{\sigma^2_{mc,\phi}}{3} = \left(\frac{\sigma^2_{\mathrm{int},\phi} + \sigma^2_{mech,\phi}}{3}\right) + \sigma^2_{align,\phi} + \sigma^2_{stab,\phi} + \sigma^2_{place,\phi} = \frac{100\mu m^2}{3} \qquad \text{in } \phi$$

and

$$\frac{\sigma^2_{mc,r}}{3} = \left(\frac{\sigma^2_{\text{int},r} + \sigma^2_{mech,r}}{3}\right) + \sigma^2_{align,r} + \sigma^2_{stab,r} + \sigma^2_{place,r} = \frac{5000\mu m^2}{3} \qquad \text{in r}$$

and

$$\frac{\sigma^2_{mc,z}}{3} = \left(\frac{\sigma^2_{mech,z}}{3}\right) + \sigma^2_{align,z} + \sigma^2_{stabz} + \sigma^2_{placez} = \frac{1000\mu m^2}{3} \text{ in z.}$$

The equation for phi implies that the intrinsic resolution of the chambers must be less than 100 µm or that the contribution from alignment and construction errors will increase the resolution of the space point of beyond the intrinsic resolution of the chamber.

<u>Accuracy of octant assemblies</u>

The octant assemblies have been designed with three alignment pins on the top and on the two sides of the frames. All external and internal alignment will be determined with respect to these pins. The pin locations are fabricated to a 25 µm absolute tolerance. In the design and fabrication of the octant assemblies we have tried to keep the distortions of the frames to as small as possible. A finite element analysis of the support frame gives a maximum distortion of the frame assembly of 30 µm on the sides and 119 µm on the top when all of the foils and wires are stretched. We are planning on prestressing the support structure to 30 µm and 119 µm when the etching and wiring is done so the uncertainty in the position of the etched strips or wires with respect to the true LCS will be comparable to optical alignment tolerances of 10 µm. The foil etching fixtures have manufacturers tolerance of 12.5 µm on the lead screw. The wire stretching jig has a measured uncertainty of 30 µm from wire to wire but a runout of approximately 200 µm. The thickness of the octant assemblies and the location of the individual planes will be limited to the buildup of adhesive and the tolerance of the manufacture of the FR4 material and it is estimated to be 200 µm. Combining the azimuthal angle uncertainties in quadrature (25,12.5,10 µm), we expect the mechanical uncertainties in the accuracys of the octant assemblies to be,

azimuthal angle accuracy of the octant assemblies	$\sigma_{\text{mech},\phi} = \sqrt{25^2 + 12.5^2 + 10^2}$	29.7 µm
radial accuracy of the octant assemblies	$\sigma_{\text{mech,r}}$	200 µm
z accuracy of the octant assemblies	$\sigma_{\text{mech,z}}$	200 µm

Once the octants are assembled we will assume that the assembly is a rigid structure. Alignment fiducials on the space frame carefully surveyed with respect to the alignment pins, will allow the octants to be aligned as a rigid body to the reference points on the magnet.

Alignment Accuracy from Station to Station

The accuracy with which the stations will be aligned depends on the precision of the active alignment monitors and their placement accuracy, and the short and long term stability of the space frame holding the octants and stations rigidly in place. Straightness monitors similar to those studied for use with the GEM detector muon system have an accuracy of 5 - 10 μm over a distance of 10 m and will be adequate for the PHENIX muon system. Stability of the octants and space frame depend on the mechanical rigidity of the space frame as well as the environmental modes induced into the magnet. These studies have not been completed but we are trying to design the space frame to have uncorrected motions due to environmental effects and mechanical rigidity to be less than 25 μm in ϕ and r and .1mm in z. Cost will more than likely define what the actual limit is. It is expected that the alignment precision and the stability for both the r and ϕ coordinates will be the same. Based on these numbers the alignment accuracys from station to station will be,

azimuthal angle accuracy of the station to station alignment	$\sigma_{\mathrm{align},\phi}$	10 μm
radial accuracy of the station to station alignment	$\sigma_{\mathrm{align,r}}$	10 μm
azimuthal angle stability of each station	$\sigma_{\mathrm{stab},\phi}$	25 μm
radial stability of each station	$\sigma_{\mathrm{stab,r}}$	25 μm.
z accuracy from station to station	σ_{z}	0.1 mm.

Initial placement Accuracy

The initial placement of the muon chamber octants depends on the method of the initial survey and on the range of the active alignment systems. For the initial survey optical alignment requires lines of sight. Lines of sight at the outer radius are possible, although difficult since we are designing the chambers after the magnet has been ‘cast in concrete’. Lines of sight will only be possible if provisions for lines of sight at the inner radius are incorporated into the design of the octant support frame for station 2. Given that station 2 is designed to allow the requisite number of lines of sight, systems such as a theodilite with averaging to get rid of distortions due to thermal air currents are required to give placement accuracys of 10 μm. The initial placement of the octants need only be within the range of the active alignment system, ~ 5 mm, but a knowledge of where the octants are with respect to the LCS must be within the optical alignment tolerance of 10 μm in ϕ. In conjunction with the initial placement by optical means the location of the octants will be determined by the active alignment system. The initial placement precision is,

azimuthal angle placement precision	$\sigma_{place,\phi}$	10 µm
radial placement precision	$\sigma_{place,r}$	10 µm
z placement precision	$\sigma_{place,z}$	10 µm

The initial placement accuracy need only be in the range of the optical and active alignment systems. We expect the placement accuracy to be,

azimuthal angle placement accuracy	$\Sigma_{place,\phi}$	5 mm
radial placement accuracy	$\Sigma_{place,r}$	5 mm.
z placement accuracy	$\Sigma_{place,z}$	5 mm.

Summary and Error Budget for LCS

The following error budget is expected:

Error	**r**	**ϕ**	**z**	
σ_{int}	0.6 mm	0.1 mm		
σ_{mech}	0.2 mm	0.03 mm	0.2 mm	
σ_{align}	0.01 mm	0.01 mm		
σ_{stab}	0.025 mm	0.025 mm	0.1mm	
σ_{place}	0.010 mm	0.010 mm	0.010 mm	(precision)
Σ_{place}	5 mm	5 mm	5 mm	(accuracy)

The error budget for r and z are well within the tolerance required by simulations. For ϕ combining the errors we get an expected space point resolution of 115 µm. To achieve a space point resolution of 100 µm, an intrinsic chamber resolution of 82 microns is required.

3 Global Alignment

The accuracy of relating the muon arm local coordinate system (LCS) to the rest of PHENIX is limited by the multiple scattering in the muon magnet steel and the initial alignment of the detector subsystems to each other. Alignment requirements of the North muon arm to the rest of the PHENIX detector, to the south muon arm, and to the beam line will be done by comparing the results from simulations. This takes into account the affects of multiple scattering and the resolution capabilities of the muon arm.

Alignment of the Muon Arm to the Rest of PHENIX

For the purposes of aligning the muon arm to the rest of PHENIX, I have assumed that the muon tracker can be considered as a rigid body.

Alignment to the Beam Line and Vertex

Alignment to the beam line and vertex is important because errors in the knowledge of these parameters translate directly into errors in the transverse momentum. The alignment tolerance on the knowledge of the beam line and vertex should be small when compared to errors that occur due to other fundamental limits such as multiple scattering.

The accuracy of the radial coordinate in the global coordinate system (GCS) to the LCS can be determined by the accuracy of the radial measurements in the chambers. The resolution of the radial coordinate in the chambers is $1\ \text{cm}/\sqrt{12}$ or 2.9 mm. Simulations confirm that a 1 cm anode spacing is adequate for preserving the mass resolution for the upsilon. As a “rule of thumb” we will assume that we want the contributions to errors in any coordinate to be a small fraction due to misalignment and will therefore be one fourth of the measured coordinate. The radial alignment tolerance is then .75 mm.

Multiple scattering in the steel and copper nose cone can be used to find the alignment tolerances in the azimuthal and polar coordinate as well as the radial alignment tolerance at station 1 between the LCS and the GCS. The energy of muons for which we want to determine multiple scattering should be the highest energy muon. If we assume that these muons originate with the decay of the Y than we will use an upper limit of 10 GeV. Given this criteria the multiple scattering in the absorber material is 12 mr and the angular uncertainty on the polar and azimuthal angle is 7 mr. Projecting this to station 1 yields an uncertainty in r of 13 mm. To keep the alignment errors in r small when compared to that from multiple scattering we can use the 1/4 rule and define the alignment tolerance in r to be 3.3 mm.

A 7 mr angular uncertainty on ϕ and θ will also define the allowable uncertainty the axis of the muon arm can be away from the beam axis, 1.75 mr from the 1/4 rule. The length of the muon arm is 4500 mm so that the position of the end of the muon arm with respect to the front of the muon arm should be known to 31.5 mm in both x and y and applying the 1/4 rule, 8mm. This implies that we would like to know the positions of each end of the muon arm magnet $8/\sqrt{2} = 5.6$ mm. in each coordinate. Since we don’t project back to a x or y coordinate in the central magnet, the error in angular coordinate of the muon magnet with respect to the true beam axis is the correct predictor of the allowed errors in the x and y coordinate. Beam position monitors (BPM) can easily measure the location of the colliding beams to much better than 5.6 mm. A possible location for BPM's would be attached to the muon magnet back plate and the support structure for the chambers at station 1.

The remaining global coordinate is z. Projecting from the spectrometer back through the magnet steel and nose cone to determine the z coordinate will be limited by the multiple scattering angle of 7 mr. Using the multiple scattering error on the projection back to the vertex and using an average angle of 20 degrees to project onto the z axis gives an error in z of 3.7 cm. Simulations have shown that resolutions in z of the position of the vertex of up to 2 cm have no effect on the mass resolution. The alignment tolerance in z will then be one fourth of 2.0 cm or 5 mm.

The Muon Tracker alignment to the beam line and the vertex is,

alignment tolerance in x an y	σ_x and σ_y	3.7 mm
alignment tolerance in z	σ_z	5 mm

Alignment to the muon ID

Comparing tracks in the Muon Tracker with tracks in the Muon ID is an important method for rejecting pions in the Muon Arm. The alignment of the Muon Tracker to the Muon ID must not degrade the ability of the track in the spectrometer to point to the track in the Muon ID. The alignment of the muon tracker to the Muon ID is limited by the multiple scattering in the muon magnet back plate and first Muon ID plate and the smallest pad size in the Muon ID. The smallest pad size is 1.0 x 2.8 degrees in theta and phi. The first Muon ID gap is at z=7250 mm so the pad dimensions are 12.7 cm x 35.5 cm. Multiple scattering from the back plate (30 cm) is 6.6 mr for 10 GeV muons which gives a projected error in x or y of 2.5 mm. This is small when compared to the pad size so the pad size determines the alignment tolerance. An alignment tolerance of 3.2 cm is sufficient.

Alignment to the South Muon Arm

The previous analysis of the alignment of the North Muon Tracker to the beam line and vertex is basically the same for the South Muon Arm. However, to consider the relationship of the South Muon Arm to the North Muon Arm the invariant mass resolution of muon pairs can be used. The invariant mass of a muon pair depends on the momenta of each particle, p_1 and p_2, and the opening angle, $\theta_{\mu\mu}$,

$$m^2 = 4p_1p_2\sin^2\left(\frac{\theta_{\mu\mu}}{2}\right)$$

The error on the missing mass is,

$$\frac{\sigma_m}{m} = \sqrt{2\left(\frac{\sigma_p}{p}\right)^2 + \sigma_{\mu\mu}^2 \cot^2\left(\frac{\theta_{\mu\mu}}{2}\right)}$$

where $\sigma_{\mu\mu}$ is the error on the opening angle and $p_1 = p_2$.

Assuming the momentum resolution to be 1.8 % then the angle term will dominate for the smallest opening angle between the North and South Muon Arm, 110 degrees. To keep the error contribution from the angle term small we can apply the 1/4 rule and equate the angle term to 1/4 of the momentum term and get $\sigma_{\mu\mu}$ = 13 mr. Since this is the difference between the two muon angles the allowed tolerance on each of the muon angles is $\sigma_\theta = 13/\sqrt{2} = 9.2$ mr. Since the 7 mr error that resulted from multiple scattering considerations is more restrictive, it will be used to define the alignment requirements for the South Muon Arm. The implication here is that aligning both muon arms to the beam line and vertex is sufficient to insure good mass resolution.

Summary of Global Alignment

A summary of the global alignment requirements are,

Alignment tolerance of North and South Muon Arm to the beam line and vertex,

σ_x	3.7 mm
σ_y	3.7 mm
σ_z	5 mm.

Alignment of Muon Arm to Muon ID

σ_x	3.2 cm
σ_y	3.2 cm
σ_z	large