GEM TN-93-348

Engineering Elements of the Muon Alignment System

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February 18, 1993

Abstract:

The muon alignment system is a complex arrangement of straight line monitors integrated with numerous, high specific stiffness detection chambers and a large, low resonant frequency, aluminum support structure. The precision tolerances with which all of these components must be installed, aligned and maintained requires meticulous and integrated analysis and design of all of the subsystems. This report summarizes the status of the engineering effort that has been completed and a status of the design in general. At present, there is an overall concept that addresses and provides reasonable engineering solutions to all of the primary alignment challenges. Precision measurement accuracies can be achieved with equipment proven with either off-the-shelf equipment or with technologies that have been successfully demonstrated in full-scale laboratory experiments. The stability of the structures have been analyzed and determined to be capable of satisfying the alignment tolerances. And a top level alignment sequence has been identified that permits rapid, and efficient installation of the alignment system in a very tight timetable. Although many engineering details remain to be completed and changes will occur as the design of all of the systems mature, a basic concept and philosophy has been established and is defined in this report.

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1.0 Introduction

The muon alignment system is a complex arrangement of straight line monitors integrated with numerous, high specific stiffness detection chambers and a large, low resonant frequency, aluminum support structure. The precision tolerances with which all of these components must be installed, aligned and maintained requires meticulous and integrated analysis and design of all of the subsystems. This report summarizes the status of the engineering effort that has been completed and a status of the design in general. At present, there is an overall concept that addresses and provides reasonable engineering solutions to all of the primary alignment challenges. Precision measurement accuracies can be achieved with equipment proven with either off-the-shelf equipment or with technologies that have been successfully demonstrated in full-scale laboratory experiments. The stability of the structures have been analyzed and determined to be capable of satisfying the alignment tolerances. And a top level alignment sequence has been identified that permits rapid, and efficient installation of the alignment system in a very tight timetable. Although many engineering details remain to be completed and changes will occur as the design of all of the systems mature, a basic concept and philosophy has been established and is defined in this report.

2.0 Local alignment

2.1 Engineering requirements

In order to satisfy the 75 micron sagitta measurement accuracy requirement it is vital that the muon superlayer chambers be precisely aligned to each other within an alignment tower. The governing alignment engineering requirements can be divided into four categories: measurement, fiducialization, strip/strip placement and layer/layer placement. These terms are illustrated in Figure 2.1.

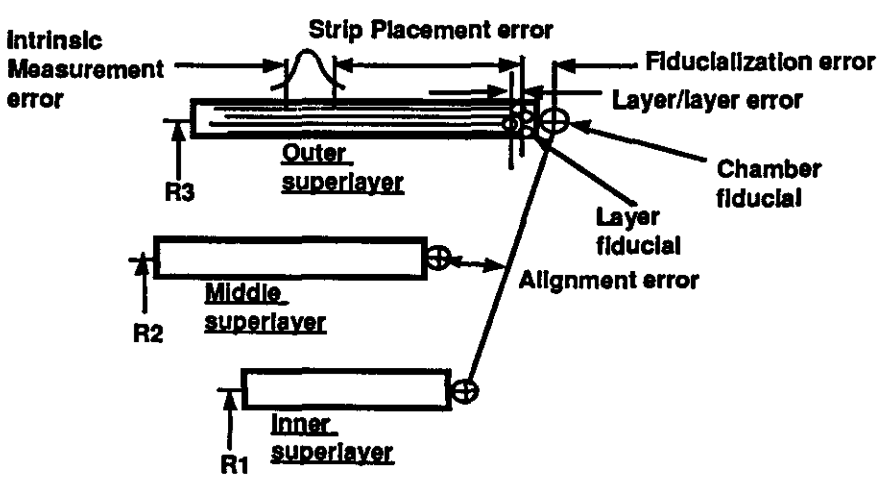


Figure 2.1 Contributing local alignment tolerances

The RMS tolerances that have been assigned to these tolerances are shown in Table 2.1. When these terms are appropriately added in quadrature and compensated for the radial location of the chambers and the number of layers in each superlayer the resulting total measurement error is less than 49 microns in the barrel region, well below the 75 micron requirement.

Error	RMS value micron
Strip to strip fiducial placement	17
Layer to layer placement	17
Fiducialization placement	10
Alignment measurement (including interpolation)	25
Intrinsic measurement	75

Table 2.1 Barrel region alignment tolerance allocation

The location of the middle superlayer relative to the inner and outer superlayers must be measured by the alignment system to better than 25 microns. The proposed Projective Alignment System (Ref. [1]) which uses LED/lens straight line monitors is capable of achieving this requirement but only if the chambers can be placed at their ideal positions within a tower to a tolerance of about 3 mm (2 mrad angularly) for the middle chambers and 5 mm (3 mrad) for the outer chambers (from A. Ostapchuk). This placement must be established prior to system activation and maintained thereafter. As long as these tolerances can be maintained then the LED/lens measurement system will be able to interpolate the track positions in the three layers with the required precision.

On each chamber, six fiducials, either a LED, lens or photosensor will be precisely located relative to the cathode strips. Any placement error between these fiducials and the strips will contribute to the total measurement accuracy. This error is added in quadrature to the intrinsic error of the superlayer and must be controlled to be less than 10 microns RMS in order to maintain overall system measurement accuracies of better than 75 microns at 500 Gev. This accurate placement will be achieved through the precision fixturing and procedures which are defined below.

Also adding in quadrature to the intrinsic layer resolution is the layer-to-layer placement accuracy of the cathode planes within a chamber. To satisfy this requirement each of the cathode planes must be precisely registered to each other to better than 17 microns RMS in the phi direction. Precision fixturing described below will be able to achieve this requirement on a rapid, high production basis.

In addition to these alignment requirements there are other chamber fabrication and assembly tolerances imposed on each of the cathode strip planes, such as strip placement, cathode plane flatness and gap uniformity.

These tolerances are considered to be chamber manufacturing issues and are not discussed in this report.

2.2 Pathways

The projective alignment system is required to be integrated into a complex truss structure that includes densely packed chambers, structural bracing elements, and utility runs all of which are competing for the same space. The alignment measuring system must fit within this crowded framework and be integrated in such a way that the impact on the active measurement volume is kept to a minimum. The selected pathways for the alignment system are described below and have been integrated with the chamber design to assure compliance with all other system requirements.

2.2.1 Barrel region

The geometrical configuration of the barrel alignment system is shown in Figure 2.2.1.1

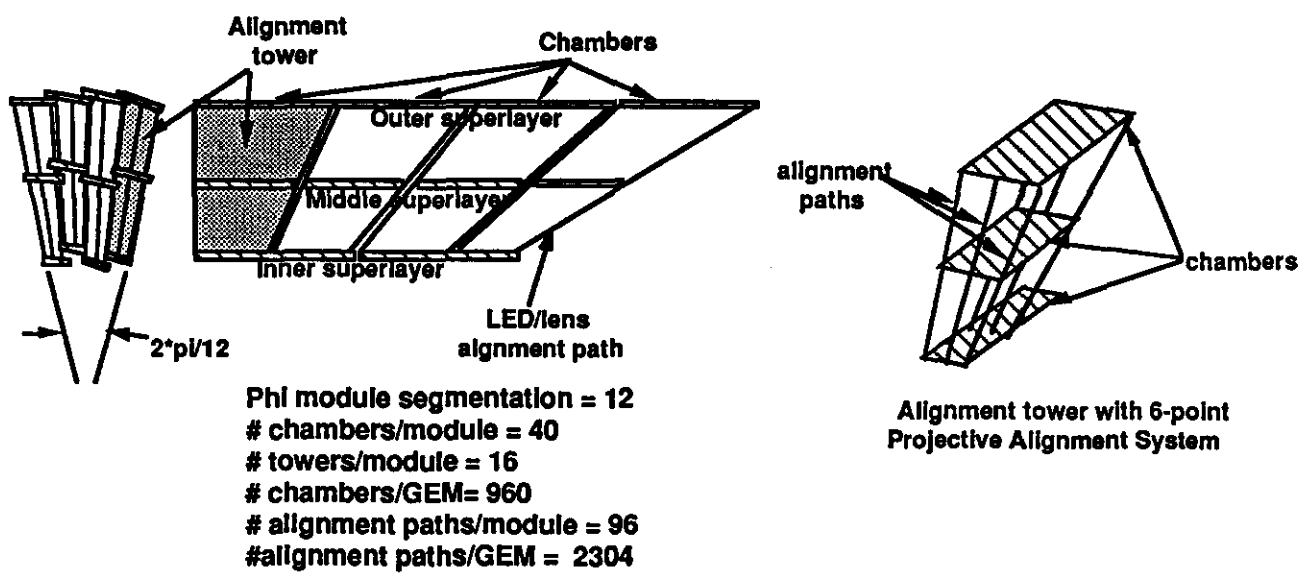
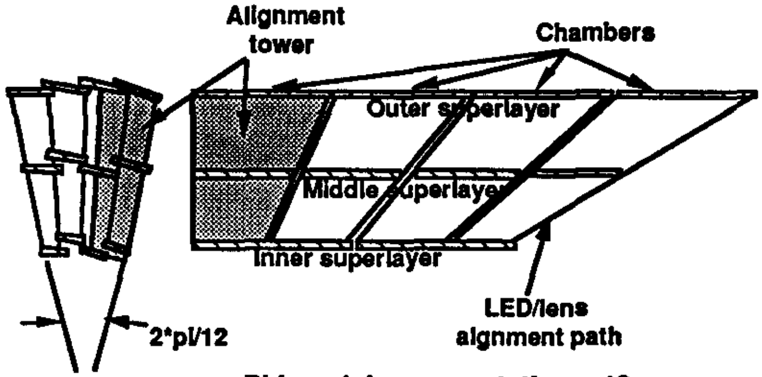


Figure 2.2.1.1 Barrel region alignment pathways

The interpolation scheme that has been proposed by Mitselmahker et. al. (Ref. [1]) requires that 6 projective alignment paths be provided for every alignment tower as shown in Figure 2.2.1.1. Three paths are located at the axial ends of each tower to permit accurate interpolation of the position of the cathode strips during rigid body motion of the chambers as well as linear and quadratic deformations. If the chambers are not coupled together to form a larger assembly, then an alignment tower is defined by the chambers in the outer layer. Presently, this establishes 16 alignment towers in each muon module resulting in 96 alignment paths per module and 2304 alignment paths for the GEM barrel muon system. Data from each set of 6 paths is independently synthesized to produce positional information for that tower. Each tower is also independently aligned. The alignment operation will be performed while each module is mounted on a service stand located in the surface facility. In this configuration each alignment tower will have good access and permit rapid assembly, installation and adjustment of each alignment pathway.

The number of alignment paths can be reduced by a factor of two by structurally linking nearby chambers together as shown in Figure 2.2.1.2. In this figure chambers pairs which are neighboring in the phi direction are coupled together to create a single, integral chamber whose structural behavior is compatible with the projective alignment system criteria. As discussed earlier this implies that expected deformations which are greater than the passive requirements must be accurately described by the linear and quadratic interpolation functions. Either rigid coupling of the chambers or creation of a secondary superstructure to which the chambers would be attached and which would maintain the required displacement tolerances are being considered. However, an engineering assessment has not yet been completed which has characterized the chamber structural performance. Therefore, the rigid coupling configuration is not presently assumed. Engineering study is underway to provide the necessary proof and if successful the baseline will be changed and significant cost savings may be realized by the resulting alignment system simplification.



Phi module segmentation = 12
 # chambers/module = 40
 # towers/module = 8
 # chambers/GEM= 960
 # alignment paths/module = 48
#alignment paths/GEM = 1152

Figure 2.2.1.2 Barrel configuration with rigidly coupled chambers

Each of the proposed alignment paths will consist of an LED, lens and photosensor, proposed by J. Paradiso (Ref. [4]). The LED and photosensor will be mounted directly to the surface of the inner and outer chambers. This can be easily accomplished with the procedures defined below and has little impact on the chamber or structure design. However, the alignment pathway must pass through the narrow space located axially between the middle chambers. The chambers are separated widely enough to accommodate the alignment path as shown in Figure 2.2.1.3.

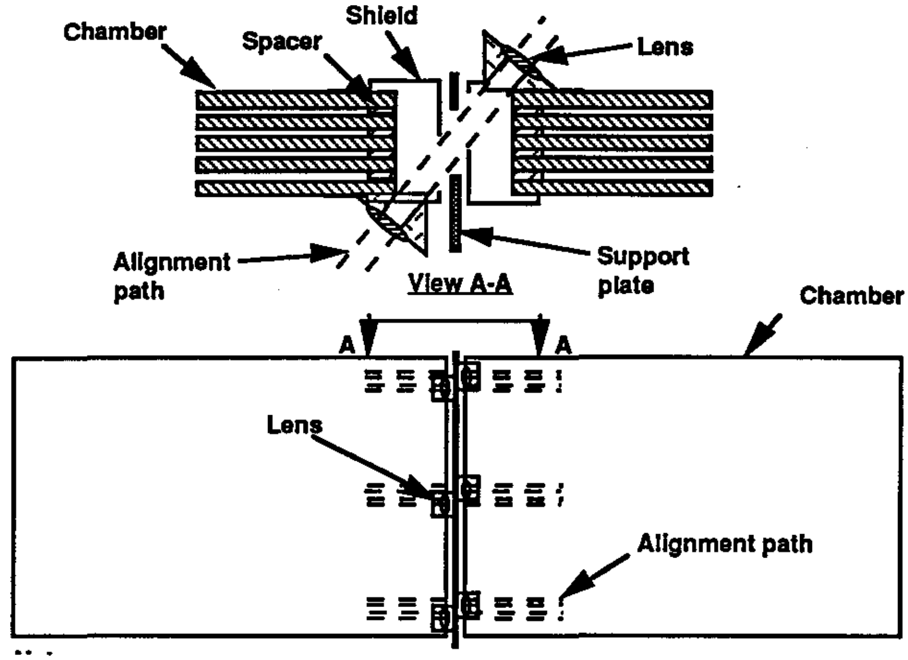


Figure 2.2.1.3 Alignment pathway between chambers

A 25 mm thick aluminum support plate, which structurally connects the truss structure above and below the middle superlayer, is located axially between interior chambers. The chambers are placed to within 25 mm of this plate to allow for installation clearances. Holes approximately 50 mm in diameter are drilled into the plate to provide a clear aperture for the LED reference beam.

2.2.2 Endcap region

The approach to endcap alignment is similar to the barrel. As shown in Figure 2.2.2.1, each endcap module is subdivided widthwise into 4 alignment towers as defined by the chambers in the outer superlayer. Since the chambers at the midplane of of the module overlap in both the phi and radial directions, there is no space through which alignment paths may be inserted. This forces an alignment tower in the endcap to be defined by the two chambers which are located along the same radial line and that these two chambers in each superlayer be rigidly coupled together. Each tower will have 3 alignment paths along the top edge (high theta) and 2 along the lower edge (low theta) of each chamber pair. This results in twelve alignment paths across the width of the module along the upper edge and 8 along the lower edge of the module. If the chamber coupling is rigid and the chambers can be accurately registered to each other, then then no additional alignment paths would be necessary. However, it is anticipated that this may be risky and so for the present, radial alignment paths, as shown, are also provided to measure the location of the midpoint relative to the outer points. If engineering analysis demonstrates that the midpoint location is predictable then these paths will be eliminated. The total alignment path count for an endcap module is 20 projective and 24 radial paths per module, and 1056 3-point monitors for all of GEM.

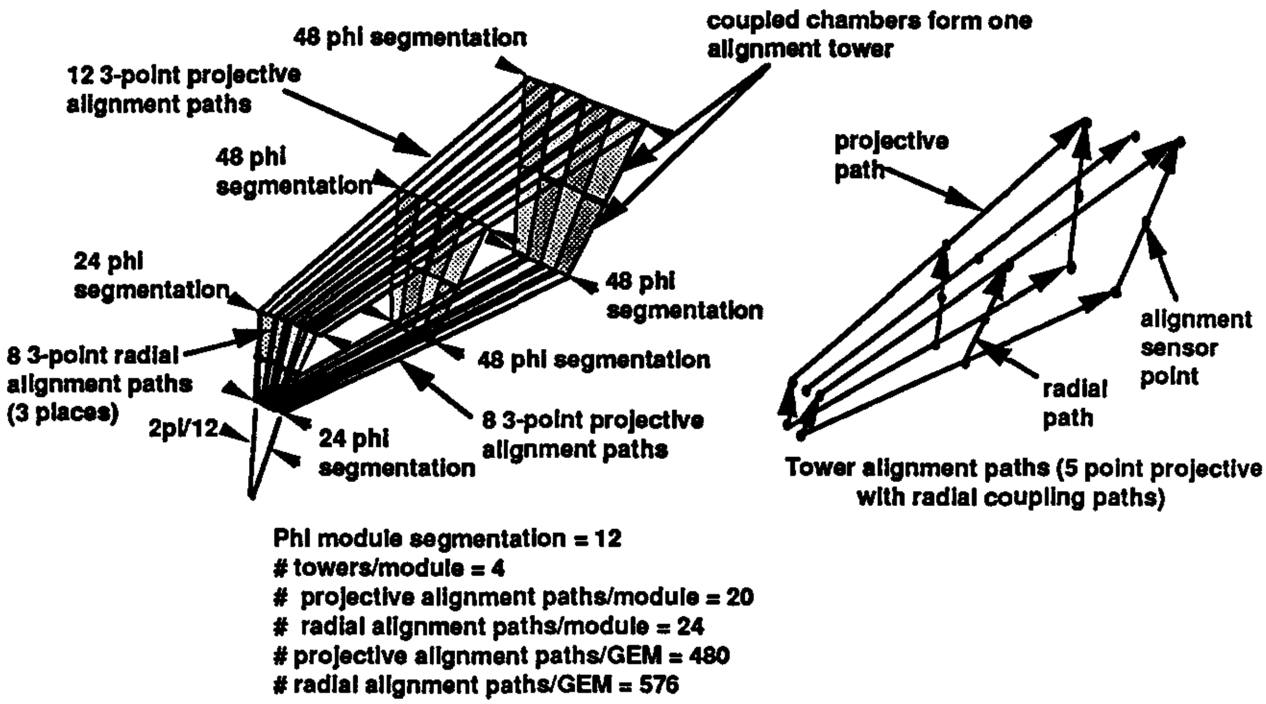


Figure 2.2.1 Endcap alignment configuration

For the endcap, cap each alignment tower is comprised of only 5 projective paths. This is in contradiction to the 6 paths recommended in Ref. [1]. Two characteristics of this system will be lost as a result of this design: 1) redundancy in the event of a failure of an alignment path monitoring system 2) ability to measure chamber torque. In addition, the impact of coupling radial alignment paths to a projective system has not yet been verified. Measurement resolution loss will have to be quantified. Significant further performance evaluation of this system is required before final design concept acceptance.

2.3 Fiducial integration

The LED, lens and photosensor of the straight line monitoring system must be placed relative to the cathode plane fiducial to within 10 micron RMS. This includes both the placement of the fiducial in its mechanical holder and the placement of the fiducial assembly onto the muon chamber. Although this requirement is very tight, the relatively small distances (1.2 meters maximum), accessibility of the cathode plane fiducial, and manufacturing precision of the fiducial holders makes the tolerance achievable.

Each of the fiducials must be first mounted into a precision holding fixture. This can be accomplished to better than 5 microns using the centering technique suggested by Paradiso et. al. This process uses a revolving stage that rotates the optical component about a centerline line defined by a LED/lens/quad cell system. The fiducial position relative to holder is adjusted at multiple angular positions until the desired concentricity is measured by the quadcell. During this process, a reference edge of the holder is maintained against a reference plane of the alignment fixture which has been precisely located with respect to the optical line-of-sight. In this way the center of the fiducial has been transfered to the mechanical edge of its holder which can now be attached to the chamber.

In order to align each of the cathode planes in a chamber relative to each other, precision washers will be located at the corner of each cathode plane. These will allow the planes to be easily referenced to a single precision surface that has been mounted perpendicular to the assembly table surface at the corner of the chamber. Onto this same assembly table other reference surfaces are added and used for the precision location of the LED/lens fiducials. Figure 2.3.1 shows the orientation of these surfaces relative to the corner reference plane. During assembly the fiducial holders will be pressed up against these surfaces to provide for rapid, accurate placement. After proper positioning has been achieved, the holder will be bolted/epoxied into place. The location of these fiducials, using the holder's reference surface, will be optically measured relative to the cathode plane fiducial to validate the placement and to provide information that could be used at a later date to compensate for interlayer placement errors.

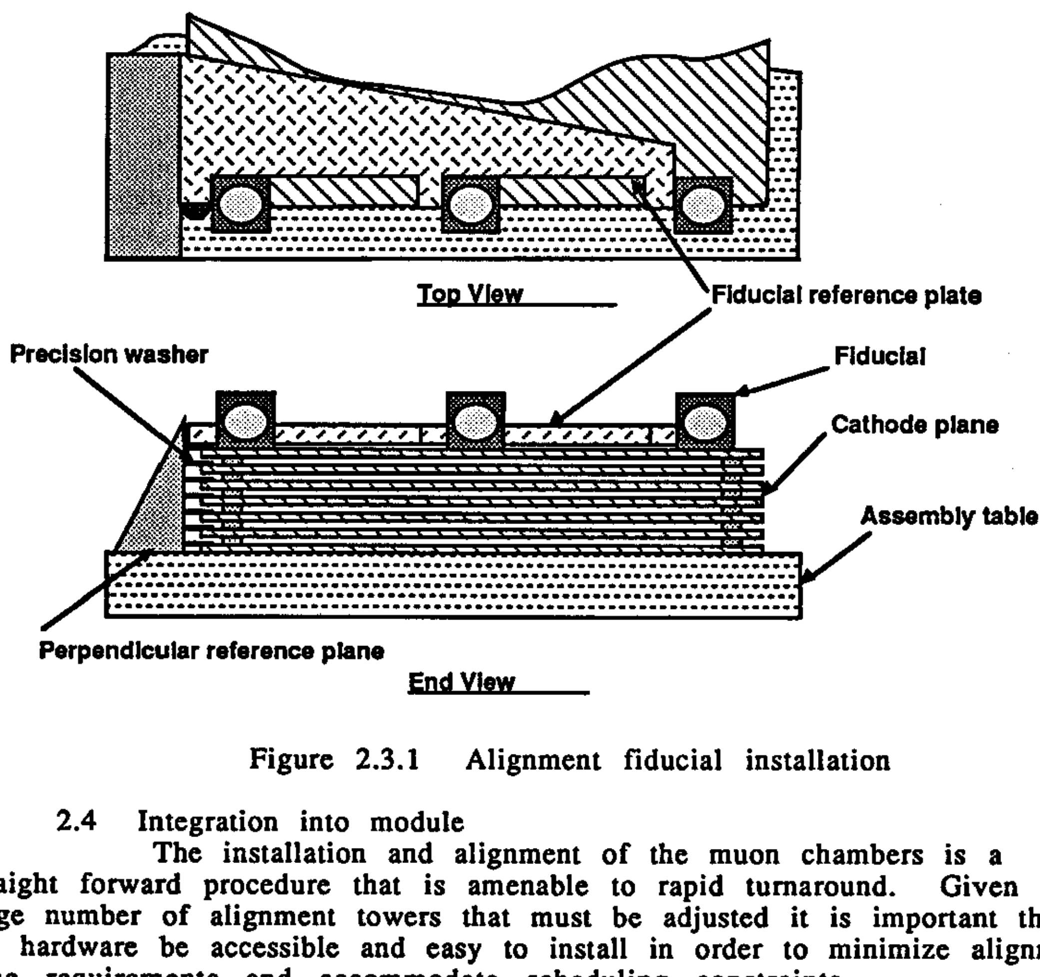


Figure 2.3.1 Alignment fiducial installation

2.4 Integration into module

The installation and alignment of the muon chambers is a straight forward procedure that is amenable to rapid turnaround. Given the large number of alignment towers that must be adjusted it is important that the hardware be accessible and easy to install in order to minimize alignment time requirements and accommodate scheduling constraints.

The chamber installation concept, Figure 2.4.1, shows that the chambers are installed and aligned on a module by module basis.

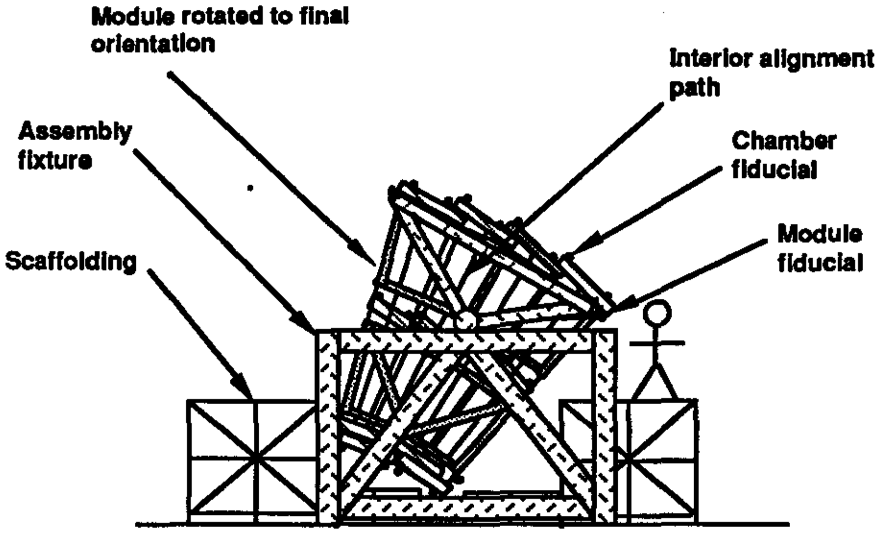


Figure 2.4.1 Module assembly and alignment

The module support structure is mounted on a rotation fixture located in the site surface facility. The structure is rotated to the angle corresponding to its final location in the experiment hall. The chambers are installed with all alignment fiducials already mounted as described in the previous section. The first alignment task will be to properly locate each chamber relative to the support structure itself. To accomplish this, auxiliary fiducials will be located on the module structure. Four would be located at the end of the module to define the trapezoidal shape of the module section. These would be located into their precise position using standard precision surveying equipment. Tolerances of better than 500 microns can be achieved. Each chamber will then be placed relative to these module fiducials. In order to to provide an accurate reference for the surveyors, auxiliary fiducials will be mounted on the chamber. Shown in Figure 2.4.2 these fiducials will be located at the corner of each chamber near the reference mark which was etched onto the cathode plane during the photolithographic process.

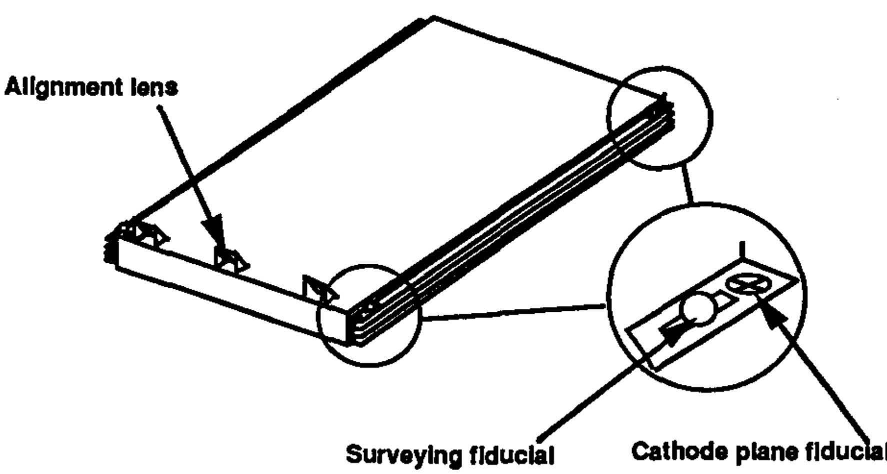


Figure 2.4.2 Survey fiducials

Due to the close proximity of these two references, positional accuracy should be better than 50 microns (better accuracy is not needed). The surveying fiducial will be a Taylor-Hobson ball or equivalent consistent with facilitating the precision surveying of many points over a 10 meter distance.

It is feasible that each chamber can be located to within about 1 mm of the module fiducials. Measurement accuracies should be better than 500 microns and adjustability of the chamber mounting mechanism can be designed to be a small fraction of a millimeter. Since the local alignment requirement (relative position of the middle superlayer relative to the outer and inner superlayers) is 5 mm this tolerance should be easily achieved at this stage of the alignment process.

At this point the alignment monitoring system will be activated. Each LED/lens system will be used to measure the straightness of each of the alignment towers and to verify that the photo sensor is centered on the LED spot. This will permit the maximum acceptable amount of alignment disruption that may be subsequently induced by either transportation, module assembly or environmental disturbances.

Adjustment of the chamber locations during this process will be accomplished by a three point kinematic mount system. Adjustability is required in at least the phi and radial directions (barrel region) to assure that both local and global alignment requirements can be satisfied (Figure 2.4.3). Further it is anticipated that remote adjustability of these degrees of freedom will be implemented to facilitate adjustment in both the surface facility and the experiment hall where access to the system will be limited. This capability is only required in two of the three layers, however. Cost considerations will determine if the third layer will be similarly equiped.

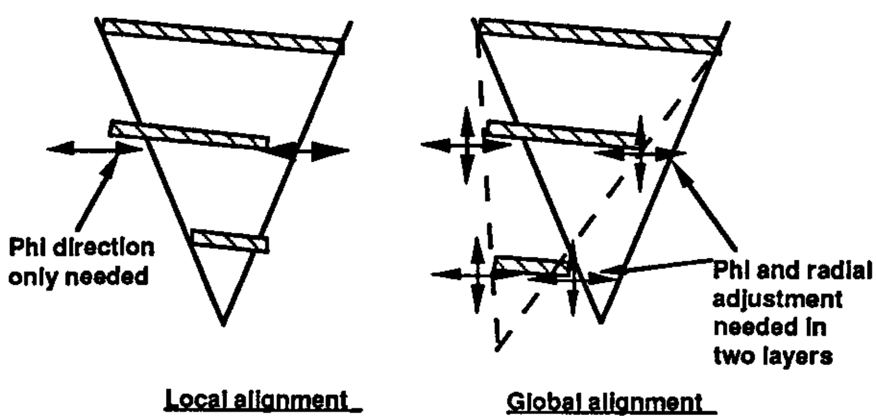
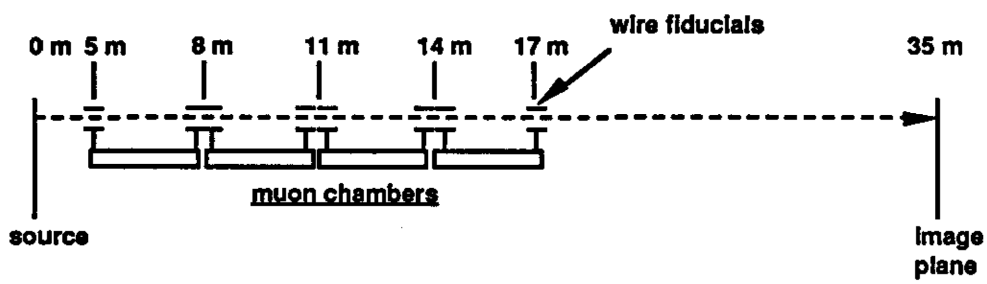


Figure 2.4.3 Chamber alignment adjustment

After the chambers have been installed and aligned in the surface facility the alignment system measurement accuracy will be verified. Several concepts have been proposed to provide this capability with 25 micron accuracy over 10 meter pathlengths. Vorobyov, Polychronakis et. al. have proposed a highly collimated x-ray source that would be propagated through the chambers which have been filled with neon. The ionization signature would be used as a straight line source. This would provide an accurate means for calibration but details of its implementation still have to be worked out.

Another x-ray technique, proven in the nuclear test program at LLNL, has also been proposed. With this technique tungsten wire fiducials would be precisely located at the corners of each chamber. A 70 Kev x-ray source would then illuminate the fiducials along a common pathlength. These could be located axially as shown in Figure 2.4.1.4 or projectively to directly verify the alignment system performance. In either case the shadows of the fiducials are measured by a CCD camera located at the end of the line-of sight. If the sensor is positioned at a point far from the last fiducial magnification of the wires at the image plane will enable precise measurement. Figure 2.4.1.4 demonstrates that better than 25 micron resolution is feasible over distances up to 17 m. This capability, in fact, has already been demonstrated at LLNL. This technique has two advantages over other optical techniques. The x-rays will penetrate the aluminum truss structure eliminating the need to provide space for the alignment path. Secondly the x-rays will not be affected by air turbulence conditions. These advantages makes this technique fundamentally very precise and worth further consideration.



Distance from source (m)	5	8	11	14	17
magnification	7	4.4	3.2	2.5	2.1
Maximum wire size -microns (in)	404 (.016)	364 (.015)	324(.013)	282(.011)	256 (.010)
image width-microns (in)	2828(.11)	1602(.064)	1036(.041)	705(.028)	538 (.021)
resolution-microns	7.1	11.4	15.6	20.0	23.8
range- mm	.69	1.23	1.79	2.3	2.8

The local alignment system will remain idle from the time of successful alignment verification until after the the modules have been assembled into the barrel structure. This process is discussed below in the global alignment section.

2.5 Structural stability

During operation the muon alignment towers will be exposed to disturbances that will perturb the original alignment. Vibrational motion caused by natural ground motion, nearby reciprocating machinery and fluid flow systems, will cause motion at a frequency faster than alignment measurement updates. Other disturbances, thermal, creep and soil upheave, will cause deflections that will vary very slowly and will be measured by the real time alignment system monitors. For the high frequency components it is important that the displacements be acceptable without correction. This then requires that vibrational disturbances be less than the 25 micron alignment measurement tolerance. A detailed dynamic analysis has been performed by Draper, LLNL and SSCL and has demonstrated compliance with this requirement. Differential displacements of the middle superlayer with the other two is projected to be about 1 micron assuming conservative ground vibration input levels.

It is important that actual ground vibration levels present during the experiment do not exceed the levels assumed in the analysis. Figure 2.5.1 shows that, if the RMS acceleration level of the random ground vibration is less than about .0001 g at a bandwidth of 20 Hz, then acceptable relative motion of the muon chambers can be expected. If the ground motion during operation exhibits an effective bandwidth greater or less than 20, then the permissible level of vibration varies according to the chart. It is important that as the GEM system and, just as importantly, the facility design matures and the construction project proceeds that all vibration sources be carefully considered and appropriate levels of isolation be provided for all equipment. It will be expensive, if not practically impossible, to retrofit solutions to vibration problems after construction has been completed.

Figure 2.5.1 is based on preliminary designs of the muon structure and assumes that the muon structure is attached to the magnet at four support points. As the design matures and the assumptions change the acceptable vibration level requirements will have to be adjusted accordingly.

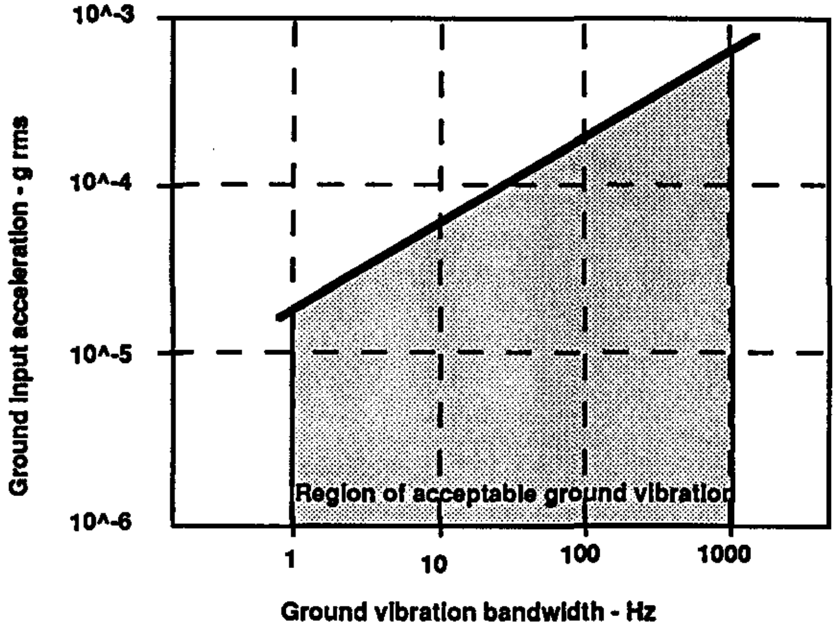


Figure 2.5.1 Assumed analysis vibration input spectrum

Slowly varying thermal distortions must not cause rigid body motion of the middle chamber relative to the inner and outer chambers greater than the range of the alignment photosensor. Presently, this range is 5 mm and perhaps even greater with new measurement techniques that have been recently proposed. A comprehensive thermal analysis has not yet been performed to confirm compliance with this requirement, however, simple hand calculations indicate that if temperatures are controlled to within 5 C that this requirement should be satisfied.

Average temperature changes of a muon chamber and temperature gradients within a chamber will affect the precision performance of the muon system. Uniform thermal expansion of the chamber will be measured by the projective alignment system and be accurately compensated by the interpolation algorithms defined by Ref. [1]. However, gradients through the thickness of the chamber will cause curling of the chamber which will cause the cathode planes to deviate from their initial flatness (Figure 2.5.2).

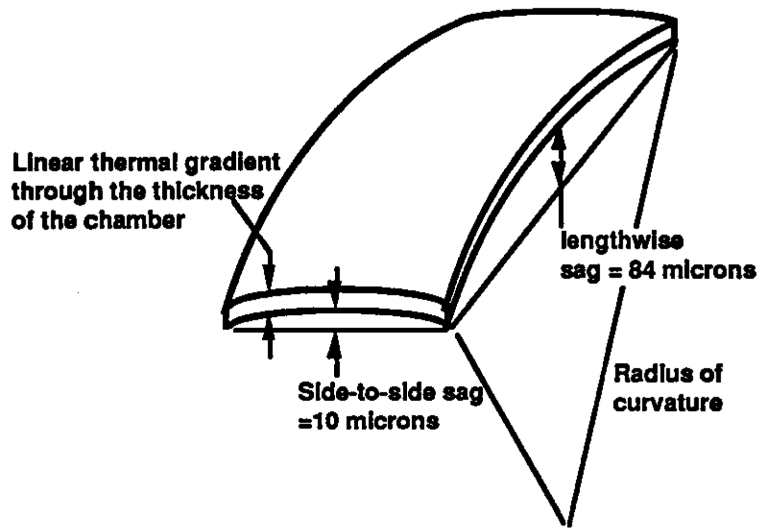


Figure 2.5.2 Thermal curling due to 1 C thickness gradient

Because of the thinness and great length of the chamber, the muon chamber will be quite sensitive to even small gradients. First order calculations have been performed which indicate that for every 1 degree Celsius of gradient, 84 microns of sag will be developed from end-to-end and 10 microns from side-to-side. The lengthwise distortion competes for the 400 micron overall flatness requirement. The side-to-side distortion will cause the anode wires to move to one side of the gas gap. In both cases the deflections are probably acceptable for a 1 degree gradient. Larger temperature differentials would not be acceptable. Careful consideration should be given to potential sources of this gradient. For example, the outer chambers will be in close proximity to the inner radius of the magnet. If the temperature of the magnet surface and the incoming cooling air are not at precisely the same temperature, then the chamber will be exposed to differential cooling on top and bottom surfaces causing the subject affect.

3.0 Global alignment

Global alignment refers to the accurate placement of each of the alignment towers relative to the interaction point, other subsystems and to other muon alignment towers. Global alignment requirements have been identified which will require alignment effort during assembly, installation into the experiment hall, and monitoring and adjustment during operation.

3.1 Engineering requirements

Ref. [4] identifies the requirement to accurately point each alignment tower towards the IP to maintain trigger road pathways. The fundamental engineering requirement is to maintain, during operation, the vertex of the alignment tower to within 5 mm, 10 mm, 5 mm of the IP in the phi, radial and axial directions respectively for the barrel region and 5 mm, 4 mm and 10 mm for the endcap. This is a placement requirement that must be monitored real time and be capable of being adjusted if deficient.

Alignment stability requirements relative to the tracker (<200 microns) are satisfied by accurate measurement, not placement. The tracker will precisely measure the IP location to within a few microns. The muon system, using background muon tracks, will accurately measure its location relative to the IP (analysis demonstrating this accuracy has not yet been completed). Slowly deviating motions will be measured by these system and accounted for in software. Non-compensable, rapid vibrational movement must be maintained below the 200 micron relative positional tolerance.

No alignment tolerances (other than assembly tolerances) between the muon and calorimeter systems have yet been identified.

The muon system will be deployed with numerous magnetic field sensors which will be accurately mounted on the chambers. The field information provided by these sensors obviates the need for precision placement of the muon system relative to the magnet.

Tower to tower alignment stability required to permit accurate track linking between decayed particles has been considered by A. Ostapchuk. Results not yet published indicate that 3 mrad relative pointing requirement between any two towers that are angularly separated by less than 45 degrees is required. This angle must be measured during assembly and then maintained by the passive stability of the muon support structure and chambers.

3.2 Tower alignment in surface facility

Global alignment of the towers is first established in the surface facility in the manner described in Figure 3.2.1.

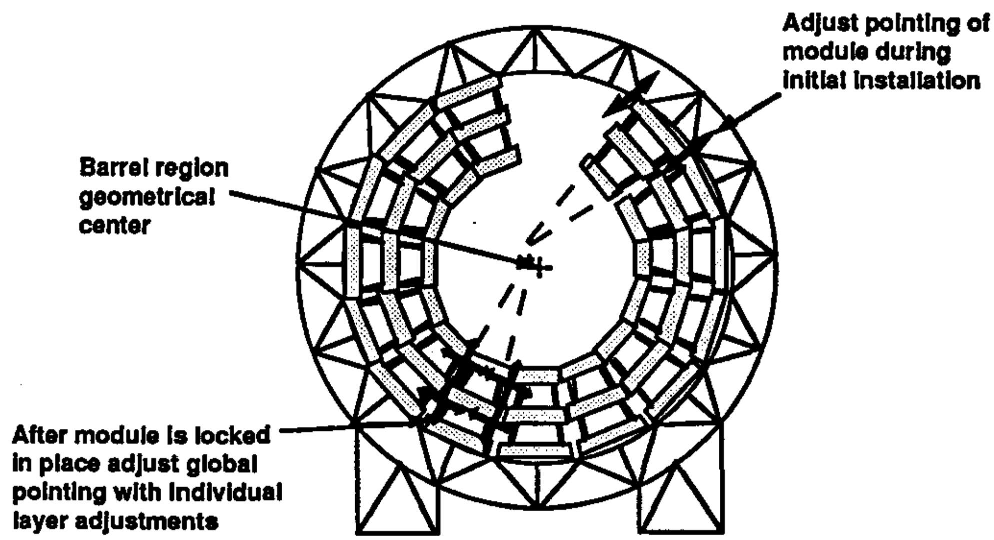


Figure 3.2.1 Global adjust mechanism locations

As the towers are installed onto the endring support structures the module support points will be adjusted to point the tower at the center of the barrel assembly. The module fiducials located on the structure (not the chambers) will be used initially to establish rough compliance. Then, using precision surveying equipment and the surveying fiducial mounted on each chamber (Figure 2.4.2), the location of each chamber will be confirmed to within 1 mm. After the barrel assembly is complete, global alignment will be reverified to assure that the alignment of towers installed early in the assembly were not disturbed. If at this point global alignment tolerances are violated remote adjustment can be made using the individual chamber support mounts on the inner and middle superlayers. Although tedious in terms of the number of towers that must be all co-aligned, the process demands resources no more sophisticated than standard surveying equipment and actuators having precision that can be achieved with off-the-shelf hardware.

3.3 Tower alignment in the experiment hall

The barrel muon structure, with all twelve modules integrated together, will be installed into the magnet as a single unit. The final position of the structure will have to be precisely adjusted to locate the center of the structure, defined by the surface facility alignment, at the anticipated location of the IP as identified by the hall alignment monuments. This adjustment will have to be performed to within a couple of millimeters. This placement error when added in quadrature to the individual chamber alignment within the muon structure and the misalignment of the experiment beam relative to the hall monuments (<2 mm) must be less than the global placement tolerance of a few millimeters.

After the muon structure has been placed into position, the location of the individual alignment towers will have to be verified. This can performed in a manner similar to the operation performed in the surface facility. Precision surveying equipment located outside of the magnet will site onto the alignment fiducials located on the individual chambers using the lines of sight identified in Figure 3.3.1.

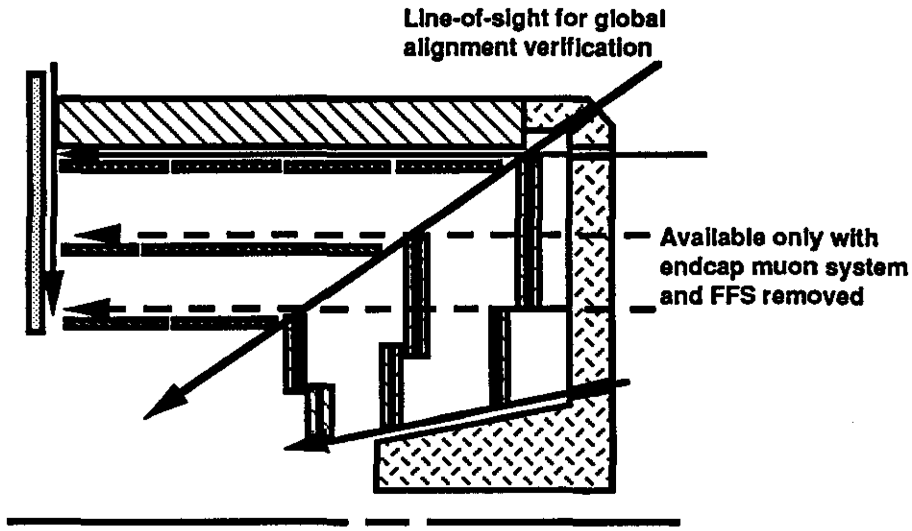


Figure 3.3.1 Lines-of-sight for global alignment verification

If the endcap structure is not in place, then chambers in all three superlayers will be visible. However, if the endcap is in position then the viewing angles will be restricted. The middle chambers will be not visible and their position must determined by some other method. In this circumstance, the tower straight line monitors can be used to determine the position of the middle chambers relative to the outer and inner chambers which are visible and can be measured with the surveying equipment. The accuracy of this process will be limited by the accuracy of the surveying equipment and the constricted viewing paths. Overall it is estimated that measurement accuracies of better than 1 mm can be achieved.

3.4 Alignment monitoring

Presently, there are no active global alignment monitoring systems proposed for the GEM system other than the detector itself. Single event, background muons can be used to identify the location of the IP relative to each alignment tower. During operation these relative positions will will be monitored. If measured values exceed criteria then correcting adjustments can be made. As discussed in Section 1.2.2 individual alignment towers are remotely adjustable using the actuators on the chambers of the inner two superlayers. Of course, these adjustments will be performed in such a way that the local straightness of the alignment tower is preserved.

3.5 Structural stability

The muon truss structure has been carefully designed to provide the maximum stability possible given the size and configuration restrictions imposed by experimental requirements. The integral truss structure provides good circumferential stiffness to maintain accurate layer to layer placement. In addition, the structure will be mounted either on the magnet near its support legs or on the experiment hall floor. In either case great effort has been directed to locate the structure on the most stable footing to minimize expected motions during operation.

The truss structure has been dynamically analyzed in great detail. Assuming conservative random vibration spectral input as discussed in Section 2.5, analytical results indicate that absolute motion of any point on the truss structure will be less than 25 microns. This will easily satisfy the global placement requirement of a few millimeters and the placement stability of 200 microns between the tracker and the muon system.

Much larger deflections will be generated by temperature variations within the muon system enclosure which is defined by the magnet. Forced air flow into the magnet will be controlled to better than 1 C, however other sources of heat including electronics and fluid flow systems will generate temperature variations greater than this. The aluminum truss structure will expand at the rate of about 23 x 10-6/C. Over the 18 meter diameter, maximum motions of 4 mm are possible with temperature increases of just 5 C. Thus, monitoring of the truss structure motion will probably be required but careful thermal management of the entire GEM system will minimize the degree to which real time adjustments will have to be made during operation. Detailed computer analysis of the muon structure is needed to characterize this behavior.

4.0 References

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