Alignment Requirements for the GEM Muon System

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Abstract:

Requirements for the local and global alignment of the GEM muon system are estimated.
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1 Introduction

Alignment requirements for the GEM muon system are determined by the required accuracy of muon kinematical variable measurements.

The GEM muon system measures the following characteristics of detected particle:

- $p_t$ - transverse momentum;
- $\phi$ - polar angle;
- $\theta$ - azimuthal angle.

Transverse momentum of particle is defined by measuring of sagitta, or deviation of hits in three muon chamber superlayers from the straight line, and angles are defined by measuring of particle coordinates in the global frame.

So, it seems natural to divide alignment requirements for the GEM muon system on the local requirements (relative alignment of superlayers) and the global one (alignment with respect to the GEM global coordinate system).

For GEM Baseline 1 analysis of the local alignment requirements was done in the work by G. Mitzelmakher and V. Zhukov (see [1]), and both local and global requirements were studied by J. Paradiso (see [2]).

As a result of these studies it was shown that the accuracy of $p_t$-measurement for high momentum particles determines very restrictive requirements for the knowing of relative chamber positions ($\sim 25\mu$ in x-direction, $\sim 100\mu$ in y-direction, $\sim 0.003$ mrad in chamber centerlines parallelism), and that the global alignment requirements are much less severe.

Method of interpolative alignment (MIA), proposed by the authors for the GEM muon system [3], makes it possible to soften drastically the requirements for chamber relative positioning and for the knowing of these positions. It was shown in [3], requirements for chamber relative displacements are of order several mm, and for relative rotations are of order several mrad.

In this work we will estimate from the MIA point of view the detailed alignment requirements, both local and global, for GEM Baseline 2 (see [4]).

Monte Carlo program, simulating chamber movements, straightness monitor measurements and trajectory of particles, produced in IP, was written.

The alignment performance of the whole detector, consisting of many towers (the GEM muon system will have about 500 towers), is characterized by the value of $\sigma_{algn}$ - dispersion of false sagitta distribution, accounting for full detector acceptance.

It seems realistic to make the assumption, that distortions of different towers (chamber shifts and rotations) are distributed uniformly within their intervals of tolerances.

The following assumptions were also made:

- uncertainty in IP z-position is $\pm 5$ cm;
- each chamber is shifted and rotated independently;
- particles are distributed uniformly inside the tower solid angle.
2 Local alignment requirements

In MIA the factors, affecting the accuracy of \( p_t \) measurement, are the followings:

- accuracy of straightness monitors;
- accuracy of monitor positioning relative to internal chamber frame (fiducialization);
- accuracy of z-coordinate measurement;
- accuracy of relative superlayers positioning:
  relative displacement tolerances;
  relative rotation tolerances;
- accuracy of straightness monitor focusing on the IP;
- chamber deformations.

The fundamental requirement for sagitta measurement error due to misalignment:

\[
\sigma_{\text{align}}^{\text{tot}} \leq 25\mu
\]  

defines the budget of different factor contributions to this value.

The requirements for each factor parameters were dictated by the restriction that the contribution of any factor \( \sigma_{\text{align}}^{i} \) to the total error \( \sigma_{\text{align}}^{\text{tot}} \) must be less than 10\( \mu \).

2.1 Accuracy of straightness monitors

The contribution of this factor to \( \sigma_{\text{align}} \) is independent on the others and is equal to

\[
\sigma_{\text{align}}^{\text{mon}} \approx 0.4\sigma_{\text{res}}^{\text{mon}},
\]  

where \( \sigma_{\text{res}}^{\text{mon}} \) is the resolution of projective straightness monitor.

The requirement

\[
\sigma_{\text{res}}^{\text{mon}} \leq 25\mu
\]  

makes the contribution of monitor errors to \( \sigma_{\text{align}} \) less than 10\( \mu \).

2.2 Accuracy of monitor positioning

This factor is a constituent part of the monitor resolution. The error in monitor positioning (fiducialization error) in \( \phi \)-direction \( \sigma_{\phi}^{\text{mon}} \) for different superlayers have to be less than

- \( \sigma_{\phi}^{\text{mon}} \leq 20\mu \) for Inner and Outer Superlayers;
- \( \sigma_{\phi}^{\text{mon}} \leq 10\mu \) for Middle Superlayer.

Accuracy of monitor positioning in \( z \)-direction \( \sigma_{z}^{\text{mon}} \) is defined by the monitor dynamic range and has to be of the order of few mm.
2.3 **Accuracy of z-coordinate measurement**

The value of this accuracy, defined mainly by chamber technology and number of chamber layers, determines the accuracy of relative muon superlayers positioning.

Worse z-coordinate resolution implies more restrictive positioning requirements.

We will estimate positioning requirements for the following assumption of Outer superlayer z-measurement accuracy:

\[ \sigma_{z}^{\text{out}} \simeq 30\text{mm}. \]  

(4)

2.4 **Accuracy of relative superlayers positioning**

The layout of muon towers for GEM Baseline II is shown in Fig.1. There are four projective towers of chambers (I - IV) in the barrel region and one projective tower (V) in the endcaps region.

Our analysis of barrel and endcaps regions shows that the requirements for relative positioning of muon superlayers are 20% more restrictive for the barrel tower IV, closest to endcap, than for barrel tower I and endcaps tower V. We propose to choose more strict requirements for tower IV as common requirements for all towers of the GEM muon system.

If we will choose Inner Superlayer as the base, it is necessary to define 12 values:

- \( D_{z}^{\text{mid}}, D_{y}^{\text{mid}}, D_{z}^{\text{mid}} \): Middle Superlayer displacement tolerances with respect to the base;
- \( R_{z}^{\text{mid}}, R_{y}^{\text{mid}}, R_{z}^{\text{mid}} \): Middle Superlayer rotation tolerances with respect to the base;
- \( D_{z}^{\text{out}}, D_{y}^{\text{out}}, D_{z}^{\text{out}} \): Outer Superlayer displacement tolerances with respect to the base;
- \( R_{z}^{\text{out}}, R_{y}^{\text{out}}, R_{z}^{\text{out}} \): Outer Superlayer rotation tolerances with respect to the base.

The sagitta error due to superlayers positioning errors \( \sigma_{\text{align}}^{\text{pos}} \) depends on all these 12 values, and we can't determine them independently, one-by-one.

Tolerances for displacements and rotations are naturally connected by the dimensions of chambers:

\[ R_{x}^{i} \sim D_{x}^{i}/(0.5L_{x}^{i}), \]  

(5)

\[ R_{y}^{i} \sim D_{y}^{i}/(0.5L_{y}^{i}), \]  

(6)

and

\[ R_{z}^{i} \sim D_{z}^{i}/(0.5L_{z}^{i}), \]  

(7)

where

- \( L_{x}^{i} \): length of chambers in \( SL_{i} \);
- \( L_{y}^{i} \): width of chambers in \( SL_{i} \);

\( i = \text{mid, out}. \)
The result of MC simulations for this assumption about rotations and displacements tolerances connection could be parametrized by the following dependence of $\sigma^\text{pos}_{\text{align}}$ on the displacement tolerances ($\sigma^\text{pos}_{\text{align}}$ in $\mu$ amd $D$ in mm):

$$(\sigma^\text{pos}_{\text{align}})^2 \approx 10(D^\text{mid}_z)^2((D^\text{mid}_y)^2 + 0.4(D^\text{mid}_y)^2) + 0.5(D^\text{out}_z)^2((D^\text{out}_y)^2 + 0.4(D^\text{out}_y)^2). \quad (8)$$

So, the dependence on $D_z$ is slightly weaker than on $D_x$ and $D_y$, but not significantly, and we will require the common value for all displacement tolerances of given superlayer.

We see that the Middle Superlayer contribution to $\sigma^\text{pos}_{\text{align}}$ is much more large, than the Outer one.

Following this strategy we estimated the chamber positioning requirements for all towers of the GEM muon system for $z$-coordinate resolution:

$$\sigma^\text{out}_z = 30\text{mm}.$$  

The results of these estimations are presented in Table 3.

**Table 1:** The requirements for accuracy of Middle and Outer Superlayers positioning in respect to Inner Superlayer ($\sigma^\text{out}_z = 30\text{mm}$)

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Units</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D^\text{mid}_z$</td>
<td>mm</td>
<td>$\pm 1.5$</td>
</tr>
<tr>
<td>2</td>
<td>$D^\text{mid}_y$</td>
<td>mm</td>
<td>$\pm 1.5$</td>
</tr>
<tr>
<td>3</td>
<td>$D^\text{mid}_y$</td>
<td>mm</td>
<td>$\pm 1.5$</td>
</tr>
<tr>
<td>4</td>
<td>$R^\text{mid}_z$</td>
<td>mrad</td>
<td>±1</td>
</tr>
<tr>
<td>5</td>
<td>$R^\text{mid}_y$</td>
<td>mrad</td>
<td>±1</td>
</tr>
<tr>
<td>6</td>
<td>$R^\text{mid}_y$</td>
<td>mrad</td>
<td>±3</td>
</tr>
<tr>
<td>7</td>
<td>$D^\text{out}_z$</td>
<td>mm</td>
<td>±3</td>
</tr>
<tr>
<td>8</td>
<td>$D^\text{out}_y$</td>
<td>mm</td>
<td>±3</td>
</tr>
<tr>
<td>9</td>
<td>$D^\text{out}_y$</td>
<td>mm</td>
<td>±3</td>
</tr>
<tr>
<td>10</td>
<td>$R^\text{out}_z$</td>
<td>mrad</td>
<td>±1.5</td>
</tr>
<tr>
<td>11</td>
<td>$R^\text{out}_y$</td>
<td>mrad</td>
<td>±1.5</td>
</tr>
<tr>
<td>12</td>
<td>$R^\text{out}_y$</td>
<td>mrad</td>
<td>±5</td>
</tr>
</tbody>
</table>

The positioning requirements for $\sigma^\text{out}_z = 15\text{mm}$ is 1.5 times less restrictive.

### 2.5 Monitor non-projectivity

There are two types of non-projectivity of straightness monitors. First, the muon tower vertex does not coincide with the interaction point (IP). The requirement for distance between the IP and the tower vertex is

\[
\text{Dist}^\text{IP}_z \leq \pm 30\text{mm}, \quad (9)
\]

\[
\text{Dist}^\text{IP}_y \leq \pm 30\text{mm}, \quad (10)
\]


2.6 Chamber deformations

Chamber gravitational sag has predictable form of chamber surface. The requirement for the maximal sag is:

\[ Sag_{max} \leq 200\mu. \]  \hspace{1cm} (12)

The requirement for layer-to-layer distance (nomex thickness) is

\[ \sigma_{thick} \leq 80\mu. \]  \hspace{1cm} (13)

These kinds of errors have systematic form, so experimental data could be used for their correction.

Estimations for the chamber non-flatness requirements are the followings:

the dispersion of correlated deviation of all layers from the plane:

\[ \sigma_{flat}^{SL} \leq 50\mu, \]  \hspace{1cm} (14)

and the dispersion of uncorrelated layer nonflatness:

\[ \sigma_{flat}^{layer} \leq 120\mu. \]  \hspace{1cm} (15)

2.7 Summary of local alignment requirements

Summary of the local alignment requirements for all factors, affecting \( \sigma_{align} \), with their contribution to the total budget of alignment errors is presented in Table 4 for option \( \sigma_{cut} = 30\, \text{mm} \).

3 Global alignment requirements

In this note we estimated the requirements for position of muon towers with respect to:

- each other;
- Interaction Point;
- central tracker;
- calorimeter;
- magnet.

The most of the requirements for knowing of these relative positions could be fulfilled with the using of real experimental data (see [6]). Hence, it defines requirements for the position stability of the GEM muon system with respect to other GEM subdetectors.
Table 2: The local alignment requirements ($\sigma_{\text{out}} = 30\text{mm}$)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Parameter</th>
<th>Requirement</th>
<th>$\sigma_{\text{align}}^{i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor resolution and</td>
<td>$\sigma_{\text{mon}}^{i}$</td>
<td>$25\mu$</td>
<td></td>
</tr>
<tr>
<td>Monitor positioning</td>
<td>$\sigma_{\text{inn,out}}^{i}$</td>
<td>$20\mu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\phi}^{i}$</td>
<td>$10\mu$</td>
<td></td>
</tr>
<tr>
<td>Monitor defocusing</td>
<td>$\text{Dist}_{z}^{ip}$</td>
<td>$30\text{mm}$</td>
<td>$10\mu$</td>
</tr>
<tr>
<td></td>
<td>$\text{Dist}_{y}^{ip}$</td>
<td>$30\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Dist}_{z}^{ip}$</td>
<td>$30\text{mm}$</td>
<td>$10\mu$</td>
</tr>
<tr>
<td></td>
<td>$D_{z}^{\text{mid}}$</td>
<td>$\pm 1.5\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{y}^{\text{mid}}$</td>
<td>$\pm 1.5\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{z}^{\text{out}}$</td>
<td>$\pm 1.5\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{z}^{\text{mid}}$</td>
<td>$\pm 1\text{mrad}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{y}^{\text{mid}}$</td>
<td>$\pm 1\text{mrad}$</td>
<td></td>
</tr>
<tr>
<td>Superlayers positioning</td>
<td>$R_{z}^{\text{mid}}$</td>
<td>$\pm 3\text{mrad}$</td>
<td>$12\mu$</td>
</tr>
<tr>
<td></td>
<td>$D_{z}^{\text{out}}$</td>
<td>$\pm 3\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{y}^{\text{out}}$</td>
<td>$\pm 3\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{z}^{\text{out}}$</td>
<td>$\pm 3\text{mm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{z}^{\text{out}}$</td>
<td>$\pm 1.5\text{mrad}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{y}^{\text{out}}$</td>
<td>$\pm 1.5\text{mrad}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{z}^{\text{out}}$</td>
<td>$\pm 5\text{mrad}$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\sigma_{\text{align}}^{\text{tot}}$</td>
<td>$25\mu$</td>
<td>$21\mu$</td>
</tr>
</tbody>
</table>
3.1 Alignment of muon towers with respect to each other

These alignment requirements are determined by necessary angle resolution for di-muon and four-muon invariant mass measurement.

We guess that the most sensitive to angle resolution process is the decay to two muons of hypothetic particle X with zero width and mass $M_X$ in interval from 50GeV to 1000GeV.

We simulated decays of these particles with MonteCarlo program, which imitates GEM transverse momentum resolution, multiple scattering of muons in calorimeter and misalignment of GEM muon towers with respect to GEM global coordinate frame.

Results of these calculations are the followings.

- Di-muon mass resolution defines mainly by the transverse momentum resolution;

- For the case of perfect global alignment of muon towers the dispersion of reconstructed di-muon mass could be approximately parametrized by the simple expression:

$$\sigma_{M_X} \geq 0.01 M_X$$

- The dispersion of $M_X$ due to global misalignment of muon towers $\sigma_{\text{align}}$ only could be parametrized by

$$\sigma_{\text{align}}^2 = \sigma_{\text{align}} M_X,$$

where $\sigma_{\text{align}}$ is the tolerance for $\phi$- and $\theta$-deviations of muon towers in radians;

- The requirement

$$\sigma_{\text{align}} \leq 3mrad$$

makes the dispersion due to global misalignment

$$\sigma_{M_X}^2 = 0.003 M_X$$

negligible in comparison with the dispersion due to limited transverse momentum resolution and multiple scattering in calorimeter.

Four-muon invariant mass resolution implies even less restrictive requirements for the value of $\sigma_{\text{align}}$.

3.2 Alignment with respect to IP

First we have to remind the requirements for muon tower monitor focusing, which were listed among local alignment requirements (see [9]/[10]/[11]).

Relative misalignment of muon tower with respect to IP is characterized by $D_y$: the impact parameter of the local tower $y$-axis and IP.

These requirements are determined by

- efficiency of trigger (for the $\Delta \phi$-trigger strategy in barrel only);

- vertex constraint for transverse momentum measurements.
3.2.1 Trigger efficiency

The efficiency of the $\Delta \phi$-trigger is limited by the multiple scattering of muons in calorimeter. Impact parameter precision was estimated by L. Rosenson ([7]). For $p_t = 50 GeV/c$-trigger this precision for the barrel region is about 10mm.

This value defines the requirement for the tower impact parameter $D_r$:

$$D_r \leq 5 mm.$$ (16)

Accounting for the programmability of the trigger this requirement for $D_r$ is the requirement for knowing, not positioning, of this parameter.

3.2.2 Vertex constraint

There are two reasons to have the muon system aligned to the IP. First, there is a significant increasing of the muon system robustness: if, e.g., a track segment in one of the SL’s is lost due to punchthrough, electromagnetic background or cracks, the vertex constrain of the order of 500-1000 $\mu m$ for the barrel muon towers and of the order of 200 $\mu m$ for the endcaps region would restore the momentum measurement with the accuracy adequate for some of the important benchmark physical processes, like $H \rightarrow Z^0 Z^0 \rightarrow 4 \mu$. The other purpose is to improve the transverse momentum resolution for $p_T > 1 TeV/c$. This requires about 200 $\mu m$ relative alignment to the IP for the barrel region too [5].

Experimental data have to be used for the determining of $D_r$. The possible procedures are discussed in [6].

Alignment of muon towers with respect to the central tracker could play the main role in the global alignment of the GEM muon system.

Determination of IP position with respect to the central tracker is much simpler than with respect to the muon system, because there are no significant multiple scattering between beam crossing and CT chambers.

If the position of muon towers with respect to central tracker is stable in the range of a hundred microns, the problem of muon towers alignment with respect to IP can be decided by two-step procedure ([5]):

- position of IP with respect to CT is determined in every run, this problem could be solve with any charge background particles instantly;

- alignment of the muon towers with respect to CT with the necessary accuracy 200$\mu$ could be performed once in the period of mutual muon system and central tracker stability.

Similarly, alignment of the central tracker and em-calorimeter can be performed with moderate statistics of electrons and positrons. So, alignment of muon system with respect to em-calorimeter (benchmark process $H \rightarrow Z^0 Z^0 \rightarrow 2e2\mu$ requires accuracy of relative $\phi$ and $\theta$ measurement of 3 mrad) will be two-step procedure again:

- relative alignment of CT and em-calorimeter is performed with $e^-$ and $e^+$;

- alignment of the muon towers with respect to CT is performed with prompt muons.
3.3 Alignment with respect to magnetic field

This issue needs more study, what factor plays the main role in $p_T$-measurement in the endcaps: the value of field strength integral along the particle trajectory only, or the detailed map of field is needed for momentum reconstruction.

The estimation of [1] gave the requirement for the radial positioning of muon chambers in the endcaps, determined by the uniformities of magnetic field, of order 2.5mm. Moreover, di-muon invariant mass constraint in decays $Z^0 \rightarrow \mu^+\mu^-$ (see [5]), $J/\psi \rightarrow \mu^+\mu^-$, $\Upsilon \rightarrow \mu^+\mu^-$ can be used for calibration of magnetic field measurement.

3.4 Summary of global alignment requirements

Summary of the global alignment requirements for the GEM muon systems is presented in Table 6.

Table 3: The global alignment requirements

<table>
<thead>
<tr>
<th>Tower with respect to</th>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>$\sigma_{\phi}^{low}$</td>
<td>3mrad</td>
</tr>
<tr>
<td>tower</td>
<td>$\sigma_{\phi}^{low}$</td>
<td>3mrad</td>
</tr>
<tr>
<td>Interaction point</td>
<td>$D_{\text{trigger}}^{\text{mag}}$</td>
<td>5mm</td>
</tr>
<tr>
<td></td>
<td>$D_{\text{robustness}}^{\text{mag}}$</td>
<td>500 - 1000µ</td>
</tr>
<tr>
<td></td>
<td>$D_{\text{resolution}}^{\text{mag}}$</td>
<td>200µ</td>
</tr>
<tr>
<td>Magnet</td>
<td>$D_{r}^{\text{mag}}$</td>
<td>±2.5mm</td>
</tr>
</tbody>
</table>

Acknowledgments

We gratefully acknowledge Mike Marx, Joe Paradiso, Rick Sawicki, Craig Wuest, Yuri Fisyak for their helpful comments on the content of this note.

References


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[7] Rosenson L., private communication
Fig. 1 Geometrical Layout of the GEM muon system