Fiducialization Precision of Mechanical Method

- A 3 GeV, 500 milliamp electron storage ring
- 20+ operational beam lines, 400 milliamp

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Outline

1. Overview
2. Magnet center based on mechanical feature
3. Magnetic center determined by vibrating wire
4. Deviation between magnetic and computed mechanical center
5. Summary
1. Overview

Table 1 Alignment Tolerances

<table>
<thead>
<tr>
<th>Tolerances</th>
<th>Magnet to magnet on a common girder</th>
<th>Girder to girder</th>
<th>Globally</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal positioning</td>
<td>± 0.030 mm</td>
<td>± 0.10 mm</td>
<td>± 3 mm</td>
</tr>
<tr>
<td>Vertical positioning</td>
<td>± 0.030 mm</td>
<td>± 0.10 mm</td>
<td>± 3 mm</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>± 0.50 mm</td>
<td>± 0.50 mm</td>
<td></td>
</tr>
<tr>
<td>Roll angle</td>
<td>± 0.50 mrad</td>
<td>± 0.50 mrad</td>
<td></td>
</tr>
</tbody>
</table>

Fiducialization
- One of the fundamental alignment tasks
- Mechanically (pole tips)
- Magnetically (integrate with rotating coil)
- Vibrating wire

Accuracy
- <100 micron (with laser tracker)
- <10 micron (with vibrating wire)

Goal:
- By comparing with vibrating wire data, estimate fiducialization precision of mechanical method.
2. Magnet Center Based on Mechanical Feature (1)

Goal of magnet survey

- Check key dimensions and make sure specification is achieved.
- Get a set of fiducial data to be used to align magnets coarsely

Features
- Pole tips
- Plane
- holes

Top plane
Pole tip
Fiducial hole
2. Magnet Center Based on Mechanical Feature (2)

Approach

- Arm
- All features
- Repeat 5 times

Accuracy

- Instrument
- Temperature (8 °C yearly)
- Fiducial type
2. Magnet Center Based on Mechanical Feature (3)

Fiducial repeatability

- Hole type
- Glued on nest

![Diagram of magnet center based on mechanical feature]

<table>
<thead>
<tr>
<th>Name</th>
<th>Nom X</th>
<th>Nom Y</th>
<th>Nom Z</th>
<th>dX</th>
<th>dY</th>
<th>dZ</th>
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</thead>
<tbody>
<tr>
<td>TOP1</td>
<td>-147.492</td>
<td>398.167</td>
<td>-522.974</td>
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<td>0.063</td>
<td>-0.005</td>
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<tr>
<td>TOP3</td>
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<td>0.063</td>
<td>-0.007</td>
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<tr>
<td>TOP2</td>
<td>147.490</td>
<td>398.162</td>
<td>-522.959</td>
<td>0.010</td>
<td>0.059</td>
<td>0.010</td>
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<tr>
<td>DS3</td>
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<td>350.199</td>
<td>-305.838</td>
<td>0.038</td>
<td>-0.031</td>
<td>0.029</td>
</tr>
<tr>
<td>US4</td>
<td>-200.018</td>
<td>350.179</td>
<td>-594.308</td>
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<td>0.039</td>
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<td>-0.051</td>
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<tr>
<td>DS1</td>
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<td>US3</td>
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<td>-594.195</td>
<td>-0.052</td>
<td>0.100</td>
<td>-0.017</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Nom X</th>
<th>Nom Y</th>
<th>Nom Z</th>
<th>dX</th>
<th>dY</th>
<th>dZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC1</td>
<td>-195.718</td>
<td>400.372</td>
<td>3028.828</td>
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<td>-0.003</td>
<td>0.000</td>
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<tr>
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<tr>
<td>QC4</td>
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<td>0.002</td>
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<tr>
<td>QC5</td>
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<td>2977.262</td>
<td>-0.003</td>
<td>0.003</td>
<td>0.001</td>
</tr>
</tbody>
</table>
2. Magnet Center Based on Mechanical Feature (5)

**Impact of computation method to magnet center**

- Selection of measured points.
- Temperature compensation
- Fiducial location

<table>
<thead>
<tr>
<th>Fiducial used</th>
<th>Eliminating bad points</th>
<th>Scale free</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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</thead>
<tbody>
<tr>
<td>Top</td>
<td>No</td>
<td>Yes</td>
<td>0.011</td>
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<tr>
<td>All</td>
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<td>No</td>
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<td>All</td>
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<td>Yes</td>
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<td>0.020</td>
<td>-0.047</td>
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<tr>
<td>All</td>
<td>Yes</td>
<td>No</td>
<td>0.017</td>
<td>0.079</td>
<td>-0.059</td>
</tr>
</tbody>
</table>
3. Magnetic Center Determined by Vibrating Wire (1)

- The line defining error. The wire center finding process had a combination errors of fiducialization, re-survey and computation which is a similar case to magnet.

- The measurement error of vibrating wire system, which was better than 10 micron.
4. Deviation between Magnetic and Computed Mechanical Center (1)

Steps to follow:

• Measure fiducials on V-notches, magnets and girder and monuments around so that all of them has location information in one coordinate system.

• Bring in the fiducial information of V-notches and magnets.

• By performing best-fit transformation the mechanical centers of vibrating wire and magnets can be computed.

• Comparing magnetic center with mechanical center, the deviation can be obtained. Since magnetic center has about 10 micron accuracy, the accuracy of the computed mechanical center can be estimated.
4. Deviation between Magnetic and Computed Mechanical Center (1)

Multiple laser tracker setup

- 12 laser tracker position.
- ~800 points
- ~4 hours
4. Deviation between Magnetic and Computed Mechanical Center (2)

Deviation

• 90 girders.

• Systematically 50 micron in elevation, RMS ~40 micron
4. Deviation between Magnetic and Computed Mechanical Center (3)

Laser tracker resolution test

- For one girder, one quadrupole was left misaligned intentionally with the offset of 
  \((0.066, 0.125)\) mm as indicated by vibrating wire.

- By performing a complete 12-tracker setup before magnet alignment, the relationship 
  between the object magnet and adjacent magnets was precisely established. This is a 
  simulation of fiducialization as the relationship between fiducials and magnetic center 
  of the magnet was established according vibrating wire data after laser tracker 
  measurement.

- 2 laser trackers were used to align the magnet by referring to the magnet fiducials.

- 6-tracker setup was used to capture the as-built information. It showed an offset of 
  \((0.0023, 0.0094)\) mm.

- As a last step, vibrating wire was used to measure the location of the quad. It showed 
  an offset of \((-0.001, 0.012)\) mm.

- Comparing the data together, the deviation between laser tracker and vibrating wire 
  is only \((-0.003, 0.003)\) mm.
Summary

• The magnets on common girder were precisely aligned by vibrating wire with very high precision achieved. The precisely aligned magnets provide accurate magnetic centers.

• The magnets were fiducialized by articulated arm by measuring the pole tips and fiducials. Since the fiducialization of magnets is just for rough alignment purpose, fiducial holes with bad repeatability were used and the temperature was loosely controlled when measurement was performed.

• By comparing the magnetic and mechanical center deviation, a deviation of ~40 micron (RMS) is found. The factors described above contribute a lot.

• It's not uncommon that similar setting of fiducials and measurement method is used in other facilities. Therefore, the result here can give a good estimate regarding the fiducial precision of mechanical method.

• To improve, good fiducials, controlled environment and precision measurement should be a minimum.
Acknowledgement

The authors would like to thank all the colleagues who contributed during the survey and alignment work.

Thanks for your attention!

Questions?