NSLS-II GIRDER PROFILING ACTIVITIES*

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Abstract
The ongoing NSLS-II project requires ±30 micron alignment tolerance to 6 or 7 main magnets in each girder assembly. A state-of-the-art vibrating wire technique used to align magnets in one girder can achieve a couple of micron accuracy. However, the transportation and manner change of supporting between magnetic measurement room and tunnel will change the girder profile, hence the magnet relative position, to the extent of bigger than ±50 micron, which makes it necessary to record and recover the girder profile. This paper will introduce the error allocation regarding error sources associated with the process firstly, and then the approach to be used to establish and reproduce the girder profile will be demonstrated. Both simulation and test results shows that ±30 micron accuracy of magnets is without doubt achievable.

INTRODUCTION
The National Synchrotron Light Source-II (NSLS-II) will be a new state-of-the-art, medium-energy electron storage ring (3 GeV) designed to deliver world-leading intensity and brightness with a 0.6 nm-rad minimum horizontal emittance when fully built out. It will provide 1 nm spatial resolution and 0.1 MeV energy resolution to facilitate the study of nanostructures. Its circumference is 792 meter. The construction of the NSLS-II’s ring building began in March 2009 and it’s scheduled to be in fully operation in June 2015. There will be 6 insertion device beamlines to be built in the first phase[1]. Table 1: Alignment Tolerances

<table>
<thead>
<tr>
<th>Tolerances</th>
<th>Magnet</th>
<th>Girder</th>
<th>Globally</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>± 0.030 mm</td>
<td>± 0.10 mm</td>
<td>± 3 mm</td>
</tr>
<tr>
<td>Vertical</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></td>
<td></td>
</tr>
<tr>
<td>Roll angle</td>
<td>± 0.50 mrad</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The above challenging ambition is one of the reasons that physics of storage ring requires ±30 micron alignment accuracy of major magnets in common girders and ±100 micron accuracy to adjacent girders, as listed in Table 1. In order to address the stringent magnets alignment requirement, vibrating wire technique is used. Transportation and repeatability tests demonstrate that ±10 micron precision is achievable [2, 3].

The magnetic measurement and alignment is conducted in an environmentally controlled room (ER). After alignment, the girders have to be transported to the tunnel and re-positioned relative to tunnel control network. The girder has 6 or 8 supports, depending on its location, which will induce the girder profile change. FEA shows 0.140 mm girder deflection due to gravity without central supports [4, 5]. Tests show that the girder profile can change as much as ±50 micron or even bigger, mostly in elevation direction, if no alignment efforts are exerted to the girder supports. It’s obvious that when girder profile changes, the alignment model will alter accordingly, to the extent that all the vibrating wire advancement could be void.

In order to reproduce the girder profile as close as possible compared with the one when magnets were magnetically aligned, the girder profile must be precisely established before leaving ER and be reproduced after arriving to the tunnel. NSLS-II survey team define this process as girder profiling. The core is to make sure that the girder vertical status keeps the same maximally.

During R&D phase, after extensive researches and tests, laser tracker technology was deemed to be capable and better than other methods such as inclinometer, autocollimator etc to handle the task during all stages of girder profiling. Although it’s a common sense that laser tracker can achieve ±30 micron or worse accuracy and any higher requirement will be a stretch, the goal is to attain ±10 micron accuracy by laser tracker.

The girder profiling topic has never been addressed before in accelerator alignment field. And the ambition to achieve ±10 micron accuracy by laser tracker is also contentious. Both of them make this topic rather meaningful.

ERROR BUDGET
In order to guarantee the ±30 micron vertical tolerance, all the error sources in the process need to be analyzed and their magnitudes need to be estimated and verified. The error sources between magnets in one girder, their magnitudes and origins are as listed below:

- Vibrating wire system error, < ±10 micron. The error magnitude is estimated based on numerous tests.
- Magnetic alignment residual error, ±6 micron. The error magnitude is a statistic of 46 girders aligned. However, the maximum residual error is 16 micron for the girders aligned [6].
- Girder profile establishment error in ER, ±9 micron. The error magnitude is a result simulated according

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to conservative laser tracker performance as will be detailed later.

- Girder profile re-measurement error in tunnel, ±9 micron. The error magnitude is a result simulated according to laser tracker’s specification which will be detailed later as well.
- The sphericity and optical centering error of SMR (spherically mounted reflector) is about ±6 micron. This is mainly represented in girder profile re-measurement step as the multiple-setup feature in ER will average out the error.
- Girder profile reproduction residual error in tunnel, ±10 micron. This error magnitude is proved to be well achievable during numerous tests. There are plans to make sure it will not add up to the existing magnetic alignment residual error and make the magnet alignment worse.

According to the law of error propagation, the final magnet alignment error is about ±20 micron. Compared to the ±30 micron tolerance, the expected final error is well under control.

**GIRDER PROFILING APPROACH**

As introduced above, the overall girder profiling process can be categorized as two major steps: profile establishment and profile reproduction. During profile establishment step, the girder profile will be measured, and its relationship with vibrating wire system will be established. Multiple tracker setups will be used to improve the accuracy. During girder profiling step, the girder profile will be reproduced with reference to the data from the former step. Two trackers will be used simultaneously to resolve the visibility problem and auto measure will be used to improve the accuracy and efficiency.

**Profile establishment**

In ER when magnetic alignment is done, survey group will take over the room and make 12 laser tracker setups to get a full understanding of the locations of vibrating wire system, girders, and magnets. The minimum shooting to each girder fiducial points is 5 times. It will cost about 6 hours to accomplish the survey task with around 1000 points taken.

Unfortunately, due to the sloppiness of magnet fiducials, they are not suitable to be used as common targets. With those points excluded, the amount of common targets is about 60. Figure 1 demonstrates the layout of the instrument and observation scheme. Leica AT901 laser tracker is staying in the room permanently for the girder profile establishment work.

With a priori 1.0 arc-second accuracy for horizontal and vertical angle, and 20 micron for distance, the average a posteriori error of girder fiducials in elevation direction is ±9 micron. Due to the extreme stable environmental condition in the room, the average a posterior vertical angular accuracy is about 0.6 arc-second which means the estimated ±9 micron accuracy is a little pessimistic.

One girder with the name of C26G4 has been measured on Oct 12 and 19, 2012 respectively for the purpose of repeatability test. With all the fixed points included, after best-fit routine, the maximum deviation magnitude is 36 micron for all the 56 points. In order to eliminate the creeping of girder and settlement of floor, the 8 girder fiducials are best-fitted. Figure 2 shows that the maximum deviation magnitude is 2 micron.

**Profile reproduction**

When the girder is moved into tunnel and positioned relative to the control network, the very last step of survey and alignment is to reproduce the girder profile. Different with the measure-only routine in ER, it’s a two-step process to reproduce the girder profile: measure it and adjust it.

The girder profile reproduction in tunnel hasn’t been officially started. The technique, tools and procedure are still in the process of developing. The following is the latest ideas regarding this crucial step.

The observation layout is shown in Figure 3. The girder fiducials at aisle side and ratchet wall side cannot be viewed by one tracker at one location due to the blocking of magnets. Therefore, two Leica AT401 laser trackers will be employed simultaneously to solve the visibility problem...
problem. In order to improve measurement accuracy, each tracker will measure the common targets and girder fiducials 4 times.

According to the manufacturer’s specification and considerably controlled environment, a priori 0.5 arc-second accuracy for horizontal and vertical angle, and 20 micron for distance are adopted to estimate the measurement error. The average a posteriori error of girder fiducials in elevation direction is also ±9 micron.

In order to automate the process, there will be SMRs pre-occupied in the nests of all the common targets and girder fiducials and pointing to the laser trackers. The operator will save a lot of efforts to move the SMR among nests. The only downside is that different SMRs might introduce errors due to sphericity and optical centering. One of the counter-measures is by measuring and comparing the SMRs to be used to minimize the impact.

The preliminary tests conducted in tunnel without strictly controlled environment show that a repeatability of around 5 micron can be achieved with the identical setup, as shown in Figure 5. The position changes of instruments will yield different girder profiles to the extent of greater than 20 micron if looking at the girder fiducials altogether. It is a reflection of the combination of the instrument error and common target geometry. Different common targets layout will be tested to further improve the performance of this approach. In spite of that, the girder profile obtained from each side of the girder is still better than 5 micron. If viewing the goal of the girder profile recovery, this is what we really care about. The impact of instrument and geometry will be embodied as girder roll or twist, in very small amplitude.

The last error source is the adjustment residual. The goal is 5 micron in R&D stage. However, it has the possibility to be inflated if it’s difficult to adjust and tight to 1000 foot-pounds which hasn’t been addressed much. Therefore, 10 micron budget is set to allow for the uncertainty.

In order to make the girder profile reproduction process efficient, a Spatial Analyzer based measurement plan (MP) is scripted. The workflow is shown in Figure 4. The MP will orient the instruments first and then generate common targets and girder fiducial groups to be used for automatic measurement. The MP will check the location of girder relative to control network before it directs the operator to do further girder profile related work. During girder profile reproduction step, the common targets and girder fiducials will have 4 sets of observations to guarantee the measurement accuracy. As a last step, the magnet fiducials will be captured and the magnet center will be computed to confirm no magnets center deviation is out of tolerance. What’s more, the magnets center deviation will give a chance of avoiding the adding up of magnetic alignment and girder profile reproduction residuals. This will be detailed right in the following part.

**Deviation check to magnetic centers**

The assumption behind NSLS-II girder assembly alignment is that there will be no movement between magnets and girder once magnets are aligned and locked. The major engineering measures are using strong bolts and nuts, locking to 300 foot-pounds etc. Intensive tests have been done to make sure the design works.
However, after long distance transportation via truck, anything could happen. The safest way to deal with it is to re-measure the magnet fiducials to see if anything abnormal ever happens after girder profile is reproduced. Due to sloppiness and visibility reasons, only top fiducials are suitable to be used for this purpose.

Dedicated MPs are devised to compute the magnetic center automatically. There are two MPs to realize the design.

The first MP will utilize the information obtained from ER to establish a baseline reference. The coordinates of magnet top fiducials and magnetic alignment residuals will be used to build ideal magnet reference files. The work can be done after girder has been measured by laser tracker in ER.

The second MP will refer to the information generated from the first MP and compare the measured information in tunnel with it. Best-fit routine will be used to compute the magnetic center deviation of each magnet and rotational information. This is basically the magnet center computation MP as shown above as the End of Figure 4.

After the execution of the MP, the magnetic center deviations can be displayed both numerically and graphically. When it’s integrated into the girder profile reproduction process, it will tell straightforwardly whether further adjustment is needed or not.

Table 2: the Deviations of Magnet Centers

<table>
<thead>
<tr>
<th>Sequence</th>
<th>DX(mm)</th>
<th>DY(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.002</td>
<td>-0.004</td>
</tr>
<tr>
<td>2</td>
<td>-0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>-0.001</td>
<td>-0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>5</td>
<td>0.008</td>
<td>-0.003</td>
</tr>
<tr>
<td>6</td>
<td>0.014</td>
<td>0.003</td>
</tr>
<tr>
<td>7</td>
<td>-0.018</td>
<td>-0.003</td>
</tr>
</tbody>
</table>

Figure 6 demonstrates a test regarding girder C26G4. Before the measurement repeatability test, the girder has been gone through transportation to the tunnel and come back again to the ER. The comparison shows the deviations of girder fiducials, magnet top fiducials and the computed magnetic centers.

The figure clearly shows that the relative positions of magnetic centers are kept unchanged with only small variations that might just be measurement noise.

The horizontal deviations can be reported as well, as listed in Table 2. However, due to the sloppiness of nests, the precision is limited. It can still trigger an alarm when there is large suspicious movement of magnet and help for further investigation.

MEASUREMENT REPEATABILITY TESTS AND VERIFICATION FROM VIBRATING WIRE

Including some of the tests that have been discussed above, some of the important tests have been done to verify the precision of girder profiling process are listed below:

- Laser tracker’s performance.
- The girder profile establishment repeatability.
- The girder profile reproduction test.
- The feasibility of using laser tracker as an indicator. Laser tracker’s performance is deemed very stable in a strictly controlled environment such as ER.

All the other tests demonstrate a smaller than ±10 micron repeatability can be achieved.

However, the ultimate check of magnet alignment accuracy is verified by vibrating wire. In order to do so, the girder needs to be aligned well and moved out and then put back into the measurement room. Laser tracker can be used to reproduce the girder profile and a new magnetic measurement can be conducted to verify the alignment. There have been three tests performed in June 2009, Oct 2011 and Mar 2012 for different girders. The first two are intending to test if there is any magnet movement during transportation from ER to tunnel, while the last one is a test of the impact of parting magnets which caused by repairing a leak vacuum chamber.

Figure 6: Vertical deviations of C26G4’s girder fiducials, magnet top fiducials and magnet centers after a round truck trip from ER to tunnel.
laser tracker system shows the girder fiducials all have deviations below ±10 micron.

The first and third tests yielded very good repeatability. The second test showed some abnormalities regarding magnetic center locations, but a subsequent repeatability measurement confirmed the measurement repeatability.

In a word, the vibrating system shows better than ±10 micron magnet center repeatability during 3 tests at different time.

**DISCUSSION**

Although it’s a common sense that laser tracker can only achieve ±30~50 micron accuracy in short range, NSLS-II survey team push the limits of laser tracker by achieving ±10 micron accuracy for each crucial step. The combination of multiple tracker setup and controlled environment helps a lot. The application of laser tracker in NSLS-II project factually extends the measurement scope of this versatile instrument.

Compared with traditional magnet assembly technique, the approach adopted by NSLS-II is one of the most precise one. It excels the method of using machining reference obviously. It’s also better than the approach of first measuring the magnet field individually and then assembly them together if the integration error caused by laser tracker or other instrument and the reproduce problem of magnets themselves are considered.

The major drawback is that the cost is high. 12-tracker setup is a luxury to capture the location of girder and magnet fiducials. Even in the tunnel 4 sets of observations to all the targets need more time and resources to accomplish it.

**SUMMARY**

The demanding ±30 micron requirement to magnets in one common girder makes it a necessity to use vibration wire technique to do the alignment. In order to resolve the deformation issue of girder after transportation and reposition, girder profiling, which is a complement to the vibrating wire technique, is proposed and applied.

The girder profiling process depends on high performance of laser tracker greatly. With controlled environment and carefully designed procedure, laser tracker can be used to achieve ±10 micron accuracy for accelerator project.

The simulations and tests prove that the ±30 micron is well achievable. Till Sep 2012, more than two third of girder assemblies have been measured and aligned magnetically in ER and the profiles have been established by 12-tracker setup. The girder profile reproduction in tunnel will be formally started sometime next year to allow for floor settlement and temperature stabilizing. The procedure for girder profile reproduction is still not finalized yet, but tests that have been done indicated promising result.

Although the task is tough, we are confident now.

**ACKNOWLEDGEMENT**

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**REFERENCES**


