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# RESEARCH ON MAGNETIC CENTER MEASUREMENT OF QUADRUPOLE AND SEXTUPOLE USING VIBRATING WIRE ALIGNMENT TECHNIQUE IN HEPS-TF

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*Abstract*

Research of vibrating wire alignment technique is one important project of HEPS Test Facility (HEPS-TF). In HEPS-TF. This paper introduces the principle of the vibrating wire alignment technique and the measurement system in brief. The magnetic center measurement of quadrupole and sextupole using vibrating wire will be introduced in detail. It concludes the measurement procedure, magnetic field distribution, measurement repeatability, sag correction and magnet adjustment measurement. The research of vibrating wire has get a better precision than the aim. The magnetic center measurement precision reach to ±3μm and the magnet adjustment error is less than 6μm.

## INTRODUCTION

High Energy Photon Source (HEPS) is a synchrotron facility proposed by Institute of High Energy Physics which will be built at north-east of Beijing in China. Vibrating wire alignment technique is aimed to align quadrupoles and sextupoles on a girder about 3~5m long with high precision to meet the extremely low emittance requirement(better than 60pm·rad) [1]. Figure 1 is one of the typical magnet and girder assembly. There are several quadrupoles and sextupoles installed on this girder. The alignment tolerance of magnets on this multipole girder should be better than ±30μm in transversal and vertical direction. In HEPS-TF, a vibrating wire measurement system was set up to research the precision of measuring the magnetic center and the alignment of this technique. According to the designed specifications, the magnetic center measurement precision should be better than ±10μm and the magnet adjustment error should be less than 15μm.

The fundamental principle of vibrating wire technique is based on Lorentz force. A single conducting wire is stretched through the magnet aperture and electrified by alternating current. The wire will vibrate for period Lorentz force. By matching the current frequency to one mode of natural frequency of the wire, the vibrating amplitude will be enhanced. And by measuring the vibrating amplitude, the magnetic field at the wire position can be got. Move the wire across the magnet aperture in transversal or vertical direction, the distribution of magnetic field and magnetic center position can be measured. According to the magnetic center position to adjust the magnet. Measure the magnetic center of all magnets installed on the multipole girder one by one, and adjust their magnetic center to a line. The more detailed theory can be found in reference [2-8].

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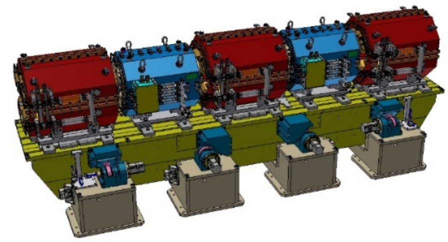

Figure 1: One of the typical magnet and girder assembly in HEPS.

## VIBRATING WIRE MEASUREMENT SYSTEM

The vibrating wire measurement system was installed in a lab with temperature stability of±0.1℃ in May, 2017 (Fig. 2). There are one sextupole and one quadrupole installed on a multipole girder. Both the magnets are borrowed from BEPCII for there are no magnets of HEPS can be used yet. Vibrating wire is stretched through mechanical center of the magnet apertures and supported by the wire supports on the two sides. The wire material is alloy of beryllium copper. Its diameter is 0.125mm.The length of the wire is about 5.5m and the wire is protected by a plexiglas tube.

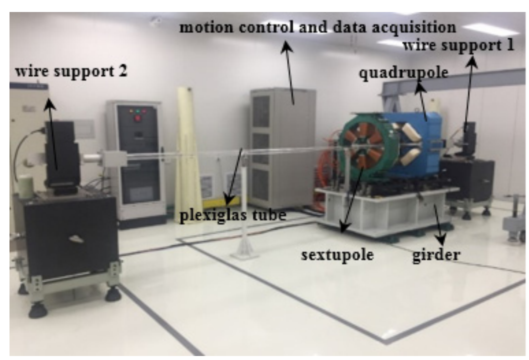


Figure 2: 5.5 meters vibrating wire measurement system.

The wire is fixed on support 1 by welding and stretched by a 1kg weight through a pulley on support 2. The wire is located by the V notch on the test benches and can move in transversal and vertical direction by the 2D translation stages. X1 and Y1 sensors on support 1 are used to detect the wire vibration in transversal direction and vertical direction separately. And another set of vibration sensor X2 and Y2 installed on support 2 are used to detect wire vibration redundantly and contrast with the test of X1 and Y1. The vibration sensor is a kind of photo-interrupter. The sensor's output voltage is linear with the wire vibration amplitude [9].

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## MAGNETIC CENTER MEASUREMENT

### *Measurement Procedures*

At first, using laser tracker to preliminary align the vibrating wire measurement system roughly, mainly concludes the wire supports, magnets and girder.

Then using vibrating wire to measure the magnetic center. Most of the magnetic center measurement procedures are carried out by an automatic program written with LabVIEW. The main procedures are as follows:

- Determination of measurement parameters.
- Measure the total magnetic field of the six measurement position when the magnet at working current.
- Measure the magnetic field of the six measurement position when the test magnet without current.
- Use the total field subtract the background field to get the real magnetic field of the test magnet, and analyse the distribution of the field to get the magnet center position.

When measuring the vertical magnetic center, sag correction should be considered.

### *Magnetic Field Distribution*

Figure 3 shows one transversal and one vertical magnetic field distribution and magnetic center measurement results of quadrupole measured by Y1 and X1 sensor. The measurement results measured by Y2 and X2 is similar to that. The total magnetic field intensity varies linearly with the wire position and the fitting line has a larger slope. The background field intensity is rather small and the slope of the fitting line is near 0. After doing background field correction , the vibrating wire only affected by the magnetic field of quadrupole. The magnetic center after background correction is located at (0.054,0.027)mm in the vibrating wire coordinate system.

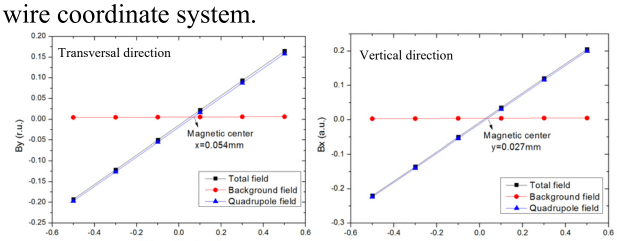


Figure 3: Magnetic field of quadrupole in transversal and vertical direction.

Figure 4 shows one transversal and one vertical magnetic field measurement result of sextupole. The distribution of total magnetic field is parabolic and the background field is linear. After doing background field correction, the distribution of sextupole magnetic field is still parabolic. The magnetic center after background correction is located at (0.028,0.175)mm in the vibrating wire coordinate system. The transversal magnetic center is affected a lot by background field for it has a larger slope. The background field with small slope has little effect on vertical magnetic center.

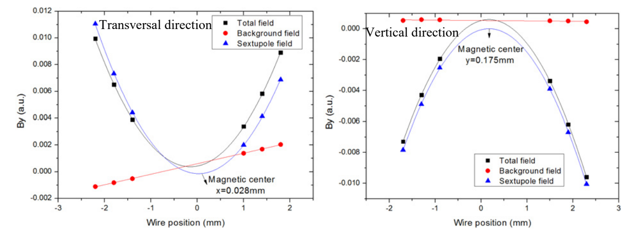


Figure 4: Magnetic field of sextupole in transversal and vertical direction.

### *The Repeatability of Magnetic Center Measurement*

In order to verify the magnetic center measurement precision, repetitive measurement is essential. 10 times consecutive transversal and vertical magnetic center have been measured. And the magnetic centres are also be measured in different days both in quadrupole and sextupole. The repeatability is shown in Table 1.

The measurement precision is pretty good both consecutive measurements and measured in different days. The quadrupole field distribution is linear and the vibration signals around the center are better than sextupole, so it is more easy to get a high precision than sextupole. Considering all the data in Table 1, the magnetic center measurement precision is better than ±3μm.

An effective method to increase the precision is improving AC signal intensity properly to improve S/N. Reduce the interruption of human activities is also necessary for the long wire is sensitive to airflow disturbance and ground vibration. Install a plexiglass tube outside the wire is effective in signal stability enhancement, especially in the condition of weak magnetic field .

Each magnet measurement will take about 50 minutes, the measurement efficiency is a bit low.

Table 1: Magnetic Center Measurement Repeatability

| **Precision (μm)** | **Quadrupole** | | **Sextupole** | |
|---|---|---|---|---|
| | **10 times** | **5 days** | **10 times** | **5 days** |
| Transversal | ± 0.3 | ± 0.7 | ± 2.4 | ± 2.3 |
| Vertical | ± 1.0 | ± 1.6 | ± 1.8 | ± 2.8 |

### *Sag Correction*

Because of the gravity, 5.5m long wire can generate a quite large of sag about 350μm. So when measuring the vertical magnetic center, sag correction should be considered. According to equation 1, sag only related with acceleration of gravity and the wire fundamental natural frequency. So sag correction can based on the measurement of wire fundamental natural frequency $f_1$. And the sag correction $s$ at the magnet position $z_{mag}$ can be calculated according to the equation 2.

$$sag = \frac{g}{32 f_1^2}. \tag{1}$$

$$s = -\frac{4sag}{l^2} z_{\text{mag}}{}^2 + \frac{4sag}{l} z_{\text{mag}}. \tag{2}$$

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In order to know the effectiveness of the wire sag correction method, an experiment was carried out to test. Table 2 shows 3 times vertical magnetic center measurement results. In this measurement, the wire fundamental natural frequencies were different because the wire was stretched by different weights. So the sag correction value *s* and the magnetic center before sag correction are all different. But after sag correction, the magnetic centres are consistent. That is a good proof of the validity of sag correction.

Table 2: Magnetic Center Measurement Before and After Sag Correction

| Weights (kg) | $f_1$ (Hz) | *s* (mm) | Magnetic center (mm) | |
|---|---|---|---|---|
| | | | Before correction | After correction |
| 1kg | 28.95 | 0.247 | 0.031 | -0.216 |
| 1.1kg | 29.3 | 0.241 | 0.026 | -0.215 |
| 1.15kg | 30.1 | 0.228 | 0.013 | -0.215 |

### *Magnet Adjustment Experiment*

In order to make sure the correctness of this vibrating wire measurement system and the effectiveness and feasibility of alignment using vibrating wire, the magnet adjustment experiment has been done. Firstly, use vibrating wire to measure the current magnetic center of the magnet ($x_0$,$y_0$). Secondly, adjust the magnet in transversal and vertical direction according to position offset of the current magnetic center to (0,0). The adjustment amount is known at the monitor of the magnet position displacement sensor. Thirdly, use vibrating wire to measure magnetic center position again to see whether the magnetic center has close to the origin of the coordinate system of vibrating wire.

Table 3 show several times of alignment adjustment experiment results. Before adjustment, the magnetic center located in different quadrant space. Each adjustment offsets and direction are different, as small as a few microns and as large as hundreds of micrometres. After adjustment, the magnetic center position offsets are all smaller than 6μm. That's a pretty good result. It is better than the aim of 15μm.

Table 3: Magnet Center Before and After Adjustment

| Magnet | Magnetic center ($x_0$,$y_0$) (mm) | |
|---|---|---|
| | Before adjustment | After adjustment |
| Quadrupole | ( 0.070, 0.009) | ( 0.003, 0.005) |
| | (-0.048,-0.043) | ( 0.004, 0.002) |
| | ( 0.057, 0.052) | (-0.002, 0 ) |
| Sextupole | (-0.144, 0.089) | ( 0.006,-0.001) |
| | ( 0.055,-0.051) | (-0.002,-0.002) |

## CONCLUSIONS

The vibrating wire system design and a series of magnetic center measurement experiments have gained good achievements. It has been proved the vibrating wire system designed reasonable and using vibrating wire to align the magnets installed on a multipole girder is feasible and can reach a high precision. The magnetic field distribution of quadrupole is more simple. It will be more easily to get a higher precision than the measurement of sextupole. A good environment with temperature stable is important for vibrating wire measurement.

The magnetic center measurement precision is better than ±3μm and the magnet adjustment error is less than 6μm. That is better than the aim of the task. Using vibrating wire technique to align the magnets installed on multipole girder in HEPS is feasible. When the magnets of HEPS are available, a formal measurement and alignment will be carried out.

## ACKNOWLEDGEMENT

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