

MAGNET FIDUCIALIZATION METHOD BASED ON SINGLE STRETCHED WIRE AND PRECISION SURFACE PLATE

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Abstract

To meet the stringent alignment tolerances of accelerator magnets for the Hefei Advanced Light Facility (HALF), accurate measurement and fiducialization of their magnetic centers are essential. This paper presents a high-precision and efficient fiducialization method developed for HALF, based on a single stretched-wire bench combined with a precision surface plate. The system enables the relative coordinates between the magnetic center and the magnet fiducials to be determined with high accuracy. Experimental results demonstrate an overall fiducialization uncertainty of better than 10 μm , satisfying the exacting requirements for magnetic center referencing in the HALF project.

INTRODUCTION

The Hefei Advanced Light Facility (HALF) is a fourth-generation diffraction-limited synchrotron radiation source under construction, consisting of a 2.2 GeV linac and a 480 m storage ring with 880 magnets. To achieve high-brightness, low-emittance electron beams, an alignment tolerance of the magnetic centers of quadrupole and sextupole magnets better than 30 μm is required, making high-precision fiducialization of the magnetic centers critical.

This paper presents a high-precision magnet fiducialization method that integrates a single stretched wire (SSW) system with a precision surface plate. By using the precision surface plate as the positional reference, the relative positions of the magnet fiducials and the magnetic center can be accurately determined.

Experimental results demonstrate that the proposed method achieves a total fiducialization error below 10 μm , thereby satisfying the stringent alignment requirements of the HALF project. Moreover, the method can be readily extended to other accelerator magnets. The measurement principle, operational procedure, and experimental results are presented in the following sections.

MEASUREMENT BENCH

To achieve efficient and reliable measurement and fiducialization of the magnetic center, an measurement bench was constructed. The system mainly consists of two parts: a stretched-wire device and a precision surface plate. The stretched-wire device is used to measure the positions of the magnetic center and multiple fiducials with high precision, while the precision surface plate serves as a positional reference for establishing the relationship between the magnetic

center and the fiducials mounted on the magnet, as shown in Fig. 1.

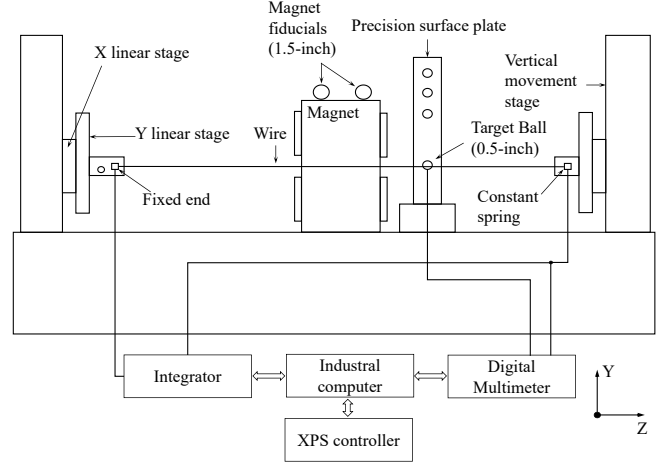


Figure 1: Layout of the measurement bench for magnet fiducialization at HALF.

MAGNETIC CENTER MEASUREMENT SCHEME

The measurement procedure has two main objectives: first, to determine the position of the magnetic center of the magnet; second, to determine the actual positions of the target balls.

Taking the measurement of the magnetic center of a quadrupole magnet as an example, the integral field of the quadrupole magnet is analytically expressed as [1]

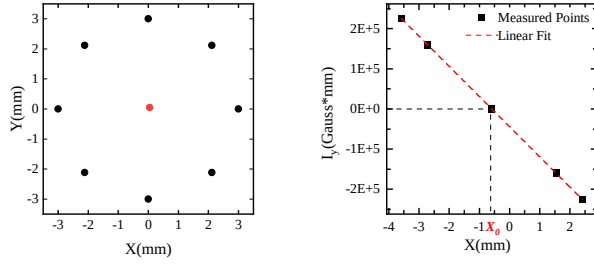
$$I_y = B_y l = G l (x - x_0), \quad (1)$$

$$I_x = B_x l = G l (y - y_0), \quad (2)$$

where x_0 and y_0 are magnetic center coordinates, x, y are the transverse coordinates in the X - and Y - directions, respectively, G is the quadrupole field gradient, and l is the effective magnetic length.

The magnetic center is defined as the position at which the integral field is zero. Therefore, for a quadrupole field, the integrated fields are measured at multiple points, and the position corresponding to a zero integrated field is obtained by fitting and identified as the magnetic center. The magnetic center measurement scheme for sextupole magnets is described in Ref. [2]. The measurement sequence (Fig. 2a) and fitting method (Fig. 2b) adopted in the actual measurement are illustrated in Fig. 2.

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(a) Magnetic center measurement (b) Magnetic center fitting method.

Figure 2: Quadrupole measurement.

MAGNETIC CENTER FIDUCIALIZATION PROCEDURE

Once the magnetic center has been measured, it is necessary to establish the positional relationship between the magnetic center and the fiducials mounted on the magnet, as shown in Fig. 3 [3].

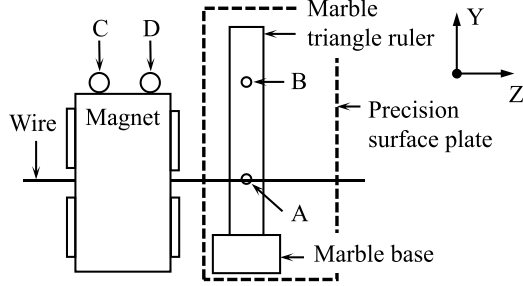


Figure 3: Schematic of the magnetic center fiducialization procedure.

Step 1: Establish the positional relationship between the magnetic center and target ball A.

After measuring the magnetic center, the precision surface plate is leveled using a precision level, and the position of target ball A on the plate is then measured using the stretched-wire device, thereby obtaining the position of target ball A relative to the magnetic center, denoted as (x_1, y_1) .

Step 2: Establish the positional relationship between target balls A and B.

Before the actual measurement, the positional relationship between target balls B and A is pre-measured using a coordinate measuring machine, denoted as (x_2, y_2) , as shown in Fig. 4. This calibration is performed only once and does not need to be repeated for each measurement.

Step 3: Establish the positional relationship between target ball B and target balls C and D mounted on top of the magnet.

The positional relationships between target ball B and target balls C and D are measured using the stretched-wire device, yielding their relative positions, denoted as (x_3, y_3) and (x_4, y_4) , respectively.

Following the above steps, the relative positions between the fiducials mounted on the magnet and the magnetic center are obtained as $(x_1 + x_2 + x_3, y_1 + y_2 + y_3)$ and $(x_1 + x_2 +$

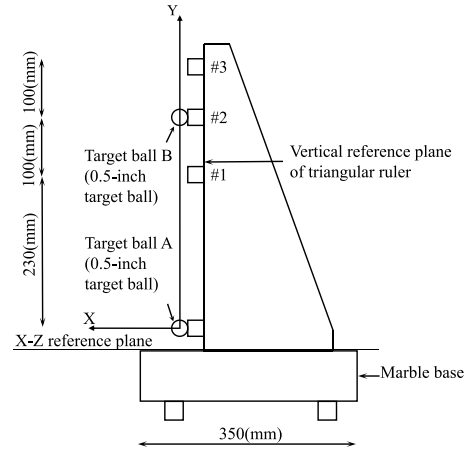


Figure 4: Pre-measurement of the positional relationship between target balls A and B.

$x_4, y_1 + y_2 + y_4)$, thereby completing the fiducialization of the magnetic center and providing accurate data for magnet alignment. To mitigate the effects of magnet pitch and yaw angles, their average value is generally adopted as the final measurement result.

MEASUREMENT FEATURES

The proposed scheme employs a stretched-wire device and a precision surface plate, offering a simple system configuration, high reproducibility, and low cost.

Using the stretched-wire device, the scheme directly measures the magnetic center and the fiducials, thereby achieving high measurement accuracy.

Because the scheme enables high-precision magnetic center measurement and fiducialization over a long travel range, it can be extended to other accelerator facilities.

Moreover, the scheme can mitigate the effect of wire sag errors that occur during long-distance measurements.

ACTUAL MEASUREMENT ACCURACY

To evaluate the actual measurement accuracy of the proposed scheme, the magnetic center and the target balls were repeatedly measured using the stretched-wire device. The measurement results for the quadrupole magnetic center and the target balls are shown in Fig. 5 and Fig. 6, respectively.

Taking the average position of the magnetic center as the reference origin, the standard deviations of the measured magnetic center positions in the X- and Y-directions were $1.3 \mu\text{m}$ and $0.7 \mu\text{m}$, respectively, as shown in Fig. 5.

For the 0.5-inch target ball (Fig. 6a), the standard deviations of the measured center positions in the X- and Y-directions were $0.6 \mu\text{m}$ and $0.4 \mu\text{m}$, respectively. For the 1.5-inch target ball (Fig. 6b), the standard deviations were $0.6 \mu\text{m}$ in both the X- and Y-directions.

OVERALL ERROR

To evaluate the error sources of the measurement system, in addition to repeated measurements of the targets, the factors that may introduce measurement errors were analyzed.

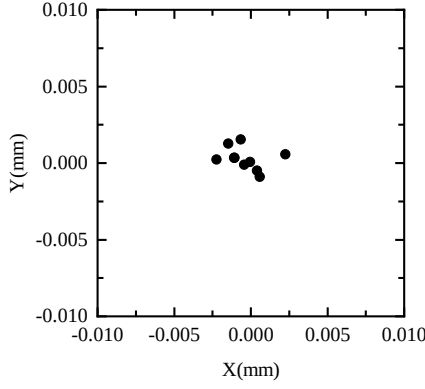
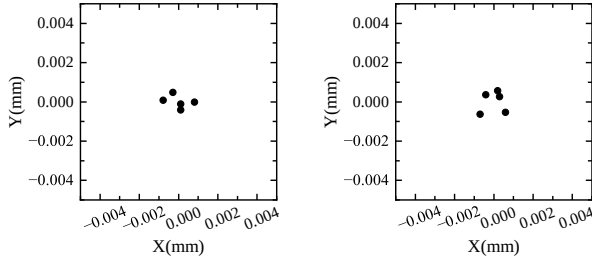


Figure 5: Quadrupole magnetic center measurement.



(a) 0.5-inch target ball measure- (b) 1.5-inch target ball measure-
ment.

Figure 6: Target ball measurement results.

The identified factors and their effects are listed in Table 1. Since the proposed scheme is insensitive to errors in the Z-direction of the targets, the Z-direction is not considered in the analysis.

Table 1: Error sources and their corresponding directions

Error Source	X	Y
Precision surface plate calibration error	3 μm	3 μm
Marble base leveling error	4.3 μm	0 μm
Magnetic center measurement error	1.3 μm	1.3 μm
Target ball measurement error	1 μm	1 μm
Linear stage position error	6.4 μm	6.4 μm

Experimental Validation of the Proposed Fiducialization Method

To verify the repeatability of the proposed method in measuring the relative positions between the magnetic center and the fiducials mounted on the magnet during actual measurements, three consecutive measurements were conducted on a quadrupole magnet. The results are presented in Table 2.

To mitigate the effects of magnet yaw and pitch angles on the measurement results, the average of the two magnetic fiducials is adopted as the reference value, and its relative position with respect to the magnetic center is subsequently calculated. To further assess the effect of realignment errors,

two independent measurements were performed on the same magnet, with realignment performed before each measurement. The corresponding results are shown in Table 3.

The measurement deviation is defined as the difference between the distances from the fiducials to the magnetic center obtained by our method and the values provided by the manufacturer. These experimental results demonstrate the system's reliable measurement accuracy and stability.

Due to time constraints on a single measurement, this paper reports only two independent measurements on the same magnet. Nevertheless, repeated measurements on multiple magnets exhibited consistent stability, validating the method described in [3].

Table 2: Results of three consecutive fiducialization measurements

Measurement number	X [mm]	Y [mm]
1	-0.0007	-0.0198
2	0.0035	-0.0182
3	-0.0006	-0.0174

Table 3: Results of two independent measurements with realignment

Measurement number	X [mm]	Y [mm]
1	0.0011	-0.0146
2	0.0081	-0.0120

CONCLUSION

This paper presents a high-precision magnetic center fiducialization scheme based on a stretched-wire device and a precision surface plate. Error analysis and experimental validation demonstrate that the fiducialization accuracy of the proposed scheme is better than 10 μm , providing a high-precision, low-cost, and extensible solution for the magnetic center fiducialization of accelerator magnets.

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