MAGNETIC CENTER MEASUREMENT AND FIDUCIALIZATION METHOD FOR HALF

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Abstract

To meet the stringent alignment requirements for accelerator magnets in the Hefei Advanced Light Facility (HALF), accurate fiducialization of the magnetic center is essential. This paper presents a high-precision and efficient fiducialization method developed for HALF, based on a single stretched wire bench integrated with a precision surface plate. The system enables precise determination of the relative coordinates between the magnetic center and the magnet fiducials. Experimental results demonstrate that the overall fiducialization accuracy is better than 10 µm, thereby satisfying the rigorous demands of magnetic center fiducialization for 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. [1] 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 PRINCIPLE

Magnetic Center Measurement Principle

For a quadrupole magnet, the magnetic center is defined as the point where horizontal and vertical dipole field components are both zero. The integral field I along the X- and Y-directions can be expressed as [2]:

$$I_y = B_y l = Gl(x - x_0), \tag{1}$$

$$I_x = B_x l = Gl(y - y_0), \tag{2}$$

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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.

By measuring the integral fields at multiple points around the magnetic center as shown in Fig. 1 (left), the measured data can be fitted to Eqs. (1) and (2). The magnetic center is then determined as the position where the integral fields are zero as shown in Fig. 1 (right).

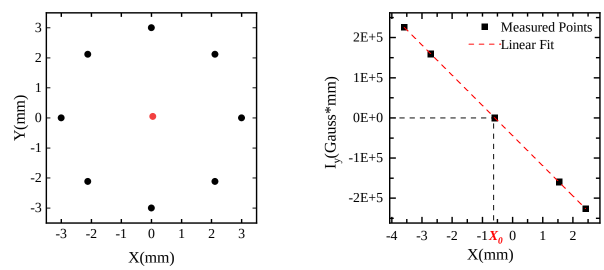

Figure 1: Magnetic center measurement method. (Left) Magnetic center measurement sequence. Black dots represent the measured points, and red dot indicates the magnetic center. (Right) Magnetic center fitting method.

Magnet Fiducialization

The layout of the measurement bench developed for magnet fiducialization in the HALF project is shown in Fig. 2. Two pairs of X/Y linear stages are arranged in a cross configuration and mounted on vertical movement stages.

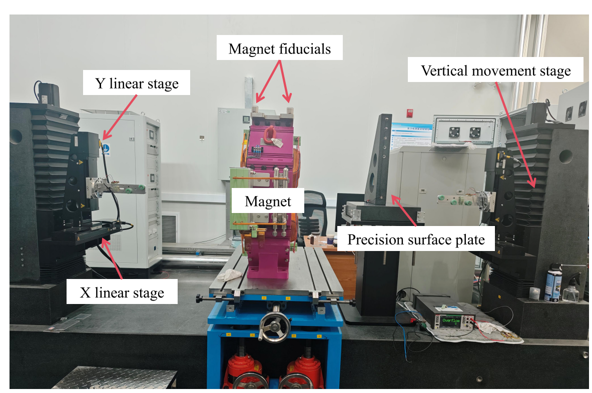

Figure 2: Layout of the measurement bench for the magnet fiducialization of the HALF.

The precision surface plate, illustrated in Fig. 3, consists of three main components: a marble base that serves as the leveling reference, a marble triangular ruler placed on the base (whose vertical alignment is ensured by the leveling of the base), and two target balls (A and B) mounted on the triangular ruler.

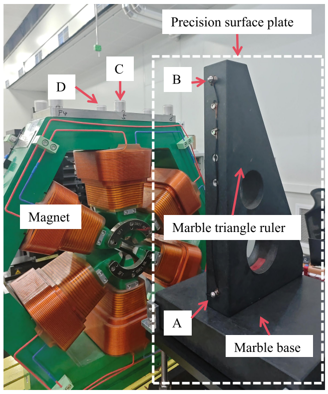

Figure 3: Schematic diagram of the precision surface plate and magnet fiducials. Two 0.5-inch target balls (A and B) are placed on the marble triangular ruler, while two 1.5-inch target balls (C and D) are positioned on the magnet fiducials.

The magnet fiducialization process as follows [3]:

- **Step 1: Relative Position Measurement of Target Ball A with Respect to the Magnetic Center**
  a) Measuring the magnetic center.
  b) Level the marble base and triangular ruler. The position of target ball A is then measured to obtain its coordinates relative to the magnetic center, denoted as (X_1, Y_1)
- **Step 2: Relative Position Measurement of Target Ball B with Respect to Target Ball A**
  The relative coordinates between the two target balls on the precision surface plate are pre-calibrated using a coordinate measuring machine (CMM), which are denoted as (X_2, Y_2).
- **Step 3: Relative Position Measurement of Magnetic Fiducials with Respect to Target Ball B**
  a) Move vertical stages to the magnet top and reinstall the stretched wire.
  b) Measure the relative position of Fiducial C with respect to Target Ball B, yielding (X_3, Y_3)
  c) Measure the relative position of Fiducial D with respect to Target Ball B, yielding (X_4, Y_4)

Calculation of fiducial coordinates relative to the magnetic center. The relative coordinates of Fiducial C with respect to the magnetic center are $(X_1+X_2+X_3, Y_1+Y_2+Y_3)$. Similarly, the coordinates of fiducial D are $(X_1+X_2+X_4, Y_1+Y_2+Y_4)$. In practice, magnet fiducialization process can be completed within one hour.

MEASUREMENT RESULTS

Magnetic Center Measurement Results

The quadrupole magnet, whose key parameters are listed in Table 1, was measured using the circular sequence illustrated in Fig. 1 (left).

Taking the average position of the magnetic center as the reference origin, the standard deviations of the measured

Table 1: Design Parameters of the Measured Quadrupole Magnet

Parameter	**Value**
Effective magnetic length	170 mm
Magnetic field gradient	43.1 T/m
Magnet aperture	36 mm

magnetic center positions in the *X*- and *Y*-directions were found to be 1.3 µm and 0.7 µm respectively, as shown in Fig. 4.

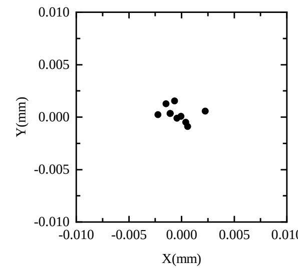

Figure 4: Measurement results of the magnetic center.

Measurement Results of Target Balls

To verify the repeatability of the center measurements, both the 0.5-inch and 1.5-inch target balls used for magnet fiducialization were measured five times each. For the 0.5-inch target ball (Fig. 5 (left)), the standard deviations of the measured center positions in the *X*- and *Y*-directions were found to be 0.6 µm and 0.4 µm, respectively. For the 1.5-inch target ball (Fig. 5 (right)), the standard deviations were 0.6 µm in both the *X*- and *Y*-directions. These results confirm that the measurement method provides sufficient accuracy for magnet fiducialization.

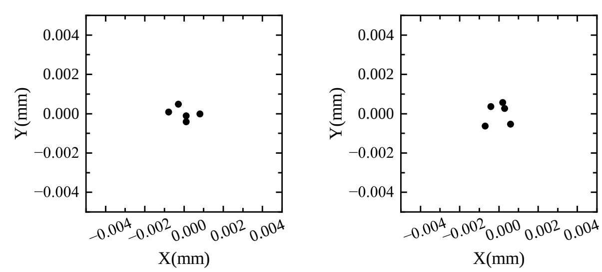

Figure 5: Measurement results of 0.5/1.5-inch target balls. (Left) Five measurements of 0.5-inch target ball center. (Right) Five measurements of 1.5-inch target ball center.

Calibration of the Relative Positions of Two Target Balls on the Precision Surface Plate

The target balls on the precision surface plate were pre-calibrated using a CMM. The CMM probed the surface of a 0.5-inch target ball to determine its center coordinates. A local coordinate system was established as shown in Fig. 6: target ball A was set as the origin, marble base surface defined the *Y*-direction, and the vertical reference plane of the triangular ruler defined the *X*-direction. Notably, target ball B can be positioned at different locations (e.g., positions #1, #2, and #3 in Fig. 6 to accommodate magnets of varying heights. Five consecutive calibrations validated ball position precision, with repeatability standard deviation less than 3 µm.

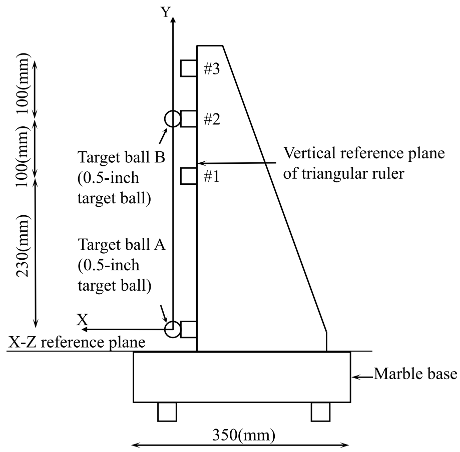

Figure 6: Calibration of target ball relative positions on the precision surface plate.

Accurate Estimation of the Magnet Fiducialization

The overall fiducialization error is calculated as:

$$\sigma = \sqrt{\sigma_{\mathrm{MC}}^2 + 3\sigma_{\mathrm{Ball}}^2 + \sigma_{\mathrm{Cali}}^2}, \tag{3}$$

where σ_{MC} is the standard deviations of magnetic center measurement, σ_{Ball} is the standard deviation of the target ball center measurement (the factor 3 accounts for three independent ball center measurements), and σ_{Cali} is the calibration error of the precision surface plate. Using the maximum values of each error component (1.6 µm for σ_{MC}, 1 µm for σ_{Ball}, and 3 µm for σ_{Cali}), the overall measurement error in the *X*- and *Y*-directions are:

$$\sigma_x = \sqrt{1.6^2 + 3 \times 1^2 + 3^2} = 3.82\,\mu\mathrm{m}, \tag{4}$$

$$\sigma_y = \sqrt{1.6^2 + 3 \times 1^2 + 3^2} = 3.82\,\mu\mathrm{m}. \tag{5}$$

Experimental Validation of the Fiducialization Method

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

To mitigate the effects of magnet yawing and pitching angles on measurement results, the average of two magnetic fiducials is adopted as the target value, and its relative position with respect to the magnetic center is subsequently calculated. To further assess the impact of realignment errors, two independent measurements were performed on the same magnet, with realignment before each measurement. The corresponding results are shown in Table 3.

The measurement result is defined as the difference between the distance from the fiducials to the magnetic center obtained in our method and the value provided by the manufacturer. These experimental results sufficiently demonstrate the system's reliable measurement accuracy and stability.

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

Table 2: Results of Three Consecutive Fiducialization Measurements

Measurement times	**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 times	**X [mm]**	**Y [mm]**
1	0.0011	−0.0146
2	0.0081	−0.0120

CONCLUSIONS

This paper has presented a high-precision magnet fiducialization method developed for the Hefei Advanced Light Facility (HALF), based on a precision surface plate integrated with a SSW system. Using this method, the positions of both the magnetic center and the fiducials are measured relative to target balls mounted on the precision surface plate. This approach enables accurate determination of the relative coordinates between the magnetic center and the fiducials. Considering all contributing error sources, the overall uncertainty of the proposed fiducialization method is less than 10 µm. The method has been successfully employed at HALF and can be readily extended to other accelerator magnets.

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