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A NOVEL BPM MECHANICAL CENTER CALIBRATION METHOD BASED ON LASER RANGING

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Abstract

Determining the mechanical center of the beam position monitor (BPM) has been a difficulty for BPM calibration. To solve this problem, a method of positioning the BPM mechanical center based on laser ranging is proposed. This method uses high-precision antenna support as the core locating datum, and high-precision laser ranging sensor (LRS) as the detection tool. By detecting the distances from the LRSs to the antenna support and the distances from the LRSs to the BPM, the mechanical center of the BPM can be indirectly determined. The theoretical system error of this method is within 20 µm, and the experimental results show that the measurement repeatability is 15 µm, This method has low cost and fast speed, which can be used for large-scale calibration.

INTRODUCTION

The BPM system, as the eyes of the particle accelerator, plays an important role in the stability of the beam orbit. About 600 BPMs are produced during the construction of High Energy Photon Source (HEPS) project [1]. Due to processing errors, the mechanical center and electrical center of BPM do not coincide. Therefore, each BPM is demanded to calibrate before use [2]. For the button-type BPM with 45-degree rotation, as shown in Fig. 1, the relationship between position coordinates and electrode signal amplitudes is defined as Eq. (1) [3].

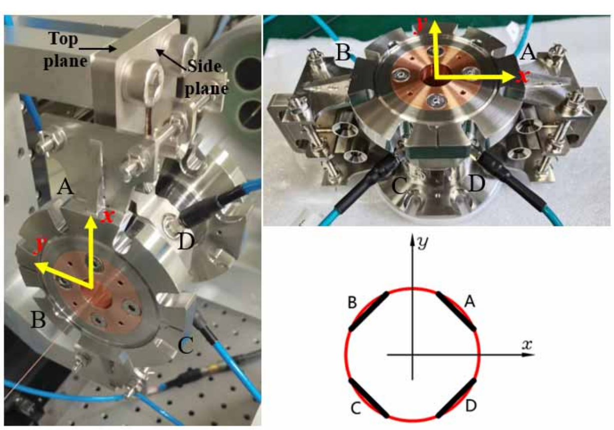

Figure 1: A HEPS BPM and its define of electrode and beam coordinate system.

$$x = K_x \frac{V_a + V_d - V_b - V_c}{V_a + V_b + V_c + V_d} + X_{\text{offset}} = K_x U + X_{\text{offset}} \quad (1)$$
$$y = K_y \frac{V_a + V_b - V_c - V_d}{V_a + V_b + V_c + V_d} + Y_{\text{offset}} = K_y V + Y_{\text{offset}}$$

where K_x, K_y are the BPM sensitivity coefficients, X_{offset}, Y_{offset} are the difference between the BPM electrical center and mechanical center. The process of determining K_x, K_y, X_{offset}, and Y_{offset} is called BPM calibration. A BPM automatic calibration system is shown in Fig. 2 and it is composed of an RF signal source, antenna (Goubau line), precision motion stages and their controller, BPM electronics, and the industrial personal computer [4, 5]. The Goubau line emits transverse electromagnetic (TEM) waves with the excitation of the RF signal source, so as to simulate the electromagnetic field of the charged particle beam in the accelerator to enable BPM calibration [5]. The BPM is driven by the precision motion stages to move in horizontal and vertical directions. The industrial computer saves the real BPM position data recorded by the controller and the calculated BPM position data from the BPM electronics. Then, the sensitivity coefficients and offsets are analyzed by the software algorithm.

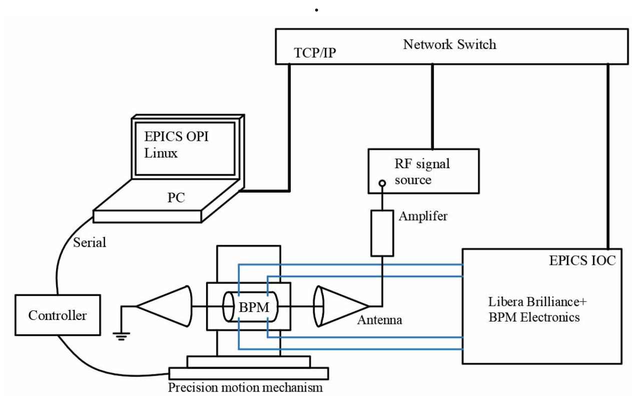

Figure 2: Schematic of BPM automatic calibration system.

In general, it is relatively easy to ascertain the BPM electrical center, as long as the operator observes the four channels of BPM electronics and makes them equal by adjusting the BPM motion stage. To achieve this goal, it is necessary to ensure that the four channels of BPM electronics and the coaxial cables are calibrated. However, finding the mechanical center is extremely difficult, so it is hard to determine X_{offset} and Y_{offset}.

A NEW APPROACH TO DETERMINING BPM MECHANICAL CENTER

The main difficulties in calibrating the mechanical center are as follows: firstly, it is not easy to ensure that the antenna is parallel to the axis of BPM; Secondly, it is almost impossible to directly measure the distance between

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the antenna and the edge of the BPM vacuum chamber; Finally, the high accuracy requirement (tens of micrometers) poses great challenges for manual adjustment. In order to solve the problems above, a high-precision antenna positioning support was designed, and a high-performance laser ranging sensor (span 30±4 mm, resolution 0.5 μm) was introduced as the detection tool for the system self-inspection and seeking BPM mechanical center. The schematic diagram of the positioning system is shown in Fig. 3, where the uppercase letters XYZ represent the geodetic coordinate system (GCS) and lowercase letters xy represent the BPM coordinate system. Figure 4 shows the distances that need to be measured to determine the BPM mechanical center, where H and L are the dimensions of BPM, H_s are the dimensions of the antenna support, r is the radius of the antenna, X_s and Y_s are the distances from the LRSs to the antenna support, and X_{bpm} and Y_{bpm} are the distances from the LRSs to BPM. When the antenna is located in the BPM mechanical center, the following relationship is satisfied:

$$Y_s + H_s = Y_{bpm} + \frac{H}{2} + r \qquad (2)$$
$$X_s = X_{bpm} + \frac{L}{2} + r$$

Transfer Eq. (2) to Eq. (3). When the position of BPM, namely X_{bpm} and Y_{bpm}, have been adjusted to meet Eq. (3), it can be considered that the mechanical center of BPM has been found.

$$Y_{bpm\_M} = Y_s + H_s - \frac{H}{2} - r \qquad (3)$$
$$X_{bpm\_M} = X_s - \frac{L}{2} - r$$

In Eq. (3), the right side of the equals sign is the parameters of the positioning system. Moreover, only Y_s and X_s are measured values, the rest are all constants. As long as the system state is unchanged, X_{bpm_M} and Y_{bpm_M} are two constants. When the antenna is in the electrical center of BPM, let the distance measured by the two laser sensors be denoted by X_{bpm_E} and Y_{bpm_E}, then the offset between the electrical center and the mechanical center can be calculated as

$$X_{\text{offset}} = -(Y_{bpm\_E} - Y_{bpm\_M}) \qquad (4)$$
$$Y_{\text{offset}} = X_{bpm\_E} - X_{bpm\_M}$$

The specific calibration operating steps are shown in Table 1.

In Table 1, step 1 is a system self-test, which only needs to be performed once as long as the system state remains unchanged. Step 2 is to make the antenna parallel to the system, and steps 3-4 ensure that the BPM is parallel to the system. Steps 5 and 6 are optional operations. If calibrating from the mechanical center, proceed to step 5. If only measuring offset, perform step 6.

ERROR ANALYSIS

The processing errors of the antenna support and BPM is the main source of system errors. Now assume that the size errors of the support and BPM are ΔH_s and ΔH, so the measured value Y_s in Eq. (3) will turn into $Y_s + \Delta H_s$, and

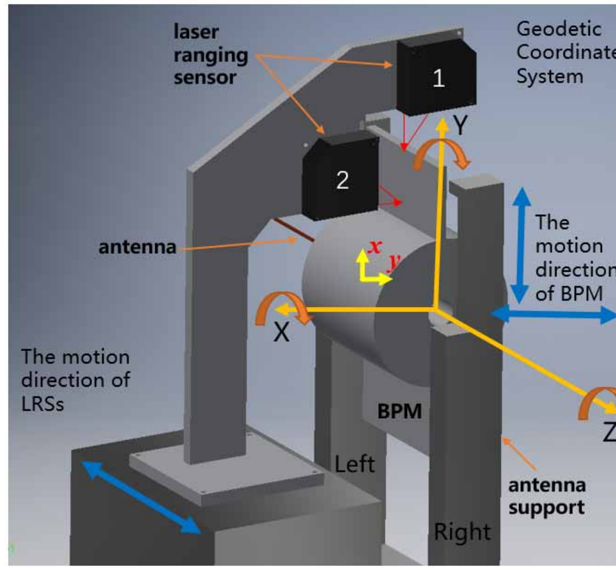

Figure 3: BPM machine center calibration method based on laser ranging.

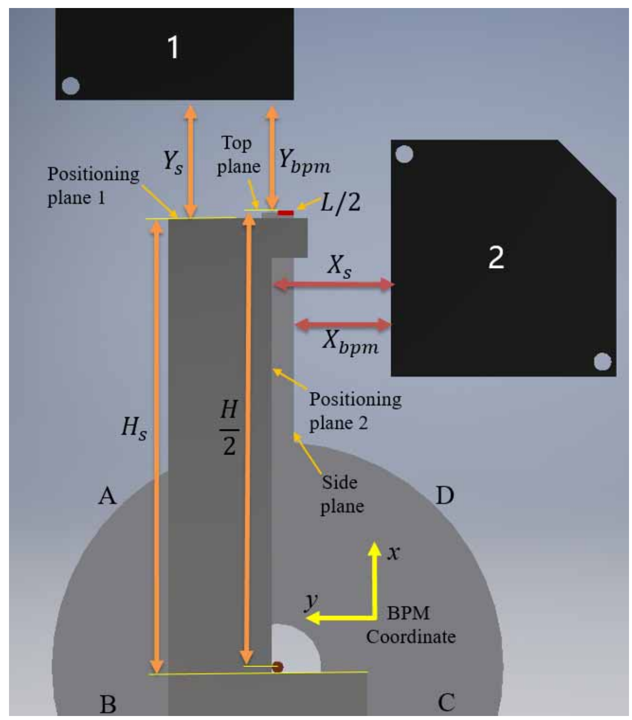

Figure 4: The distances that need to be measured to determine BPM mechanical center.

Y_{bpm_E} will become $Y_{bpm\_E} + \Delta H$. Then, the offset in the Y direction is $X'_{\text{offset}} = X_{\text{offset}} + \Delta H_s - \Delta H$. Similarly, $Y'_{\text{offset}} = Y_{\text{offset}} + \Delta L - \Delta F$, where ΔL is the size error of the BPM in the X direction, and ΔF is the geometry error of the support's positioning plane. The error model is shown in Fig. 5.

Considering the worst-case scenario, when the error direction of the antenna support is opposite to the BPM, the total systematic errors are the sum of absolute values:

$$\Delta X^s_{\text{offset}} = |\Delta H_s| + |\Delta H| \qquad (5)$$
$$\Delta Y^s_{\text{offset}} = |\Delta L| + |\Delta F|$$

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Table 1: The Steps to Determine the BPM Mechanical Center

Step Number	Operating Items	Operation Purposes
1	Move the LRSs in the Z-direction from the leftmost to the rightmost of the antenna support, and observe whether the data of the two LRSs change	Ensure that the movement direction of the LRSs is parallel to the two positioning planes (shown in Fig. 4) of the antenna support. Then, calculate X_{bpm_M} and Y_{bpm_M} based on Eq. (3).
2	Install BPM. Let the antenna through the BPM vacuum chamber and press it on the positioning planes of the antenna support.	Ensure that the antenna between the two pillars of the support is parallel to the two positioning planes.
3	Move the LRSs in the Z direction, scan the top and sides planes (shown in Fig. 4) of the BPM, and observe whether the readings of the two LRSs change.	Ensure that the axis of the BPM is parallel to the antenna (Eliminating the rotational errors around X-axis and Y-axis)
4	Hold the LRSs at the middle position of the antenna support, move BPM along the Y-axis, and observe whether the reading of the No. 2 LRS changes	Ensure that BPM is placed vertically (Eliminating the rotational error around Z-axis)
5	Adjust the position of BPM so that the distances between BPM and LRSs are equal to X_{bpm_M} and Y_{bpm_M}, which means that the antenna is in the BPM mechanical center at this time.	Align the antenna with the BPM mechanical center, open the automatic calibration software and start the calibration program.
6	Adjust BPM and let the antenna reach its electrical center, read the two LRSs data X_{bpm_E} and Y_{bpm_E}, and calculate offsets according to Eq. (4).	Only measure the electro-mechanical offset

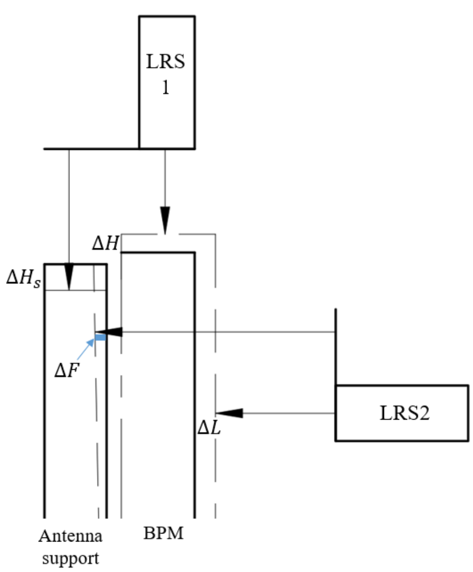

Figure 5: Schematic diagram of system error.

Since the machining error of both antenna and BPM is within 10 μm, the maximum system error is less than 20 μm.

The random error of this method includes the measurement resolution (0.5 μm) of the LRSs, the displacement accuracy (1 μm) of the motion stage, the influence of temperature drift or ground vibration, and the installation repetitive error of the BPM. Among them, the first three are small enough so as to be ignored, while the BPM installation errors will affect the electrical center parameters X_{bpm_E}, Y_{bpm_E}, and the mechanical center parameters X_s, Y_s. which means that installation errors are the main source of random errors.

Installation errors resulting in imperfect parallel within the system that causes rotation errors in in the X, Y, and Z planes of the BPM coordinate system. Theoretically, if steps 3-4 in Table 1 are strictly executed, all installation errors will be eliminated, but the calibration efficiency will be seriously reduced in actual engineering. Therefore, in order to improve calibration efficiency, the BPM installation errors were analyzed without performing steps 3-4, and the results are shown in Table 2. The error generated by rotation around the Z-axis is shown in Fig. 6.

Hence, excluding the errors that can be software eliminated, the measured random errors can be expressed as Eq. (6):

$$\Delta Y^{r}_{\text{offset}} = \Delta X^{rx}_{bpm\_E} + \Delta X^{ry}_{bpm\_E} + \Delta X^{rz}_{bpm\_E} + \Delta X^{rz}_{s} \quad (6)$$
$$\Delta X^{r}_{\text{offset}} = \Delta Y^{rx}_{bpm\_E} + \Delta Y^{ry}_{bpm\_E} + \Delta Y^{rz}_{bpm\_E} + \Delta Y^{rz}_{s}$$

Assuming that $\theta_z = 0.1°$, $l_3 = 4$ mm, $l_4 = 50$ mm, and $H = 210$ mm, the error value $\Delta X^{rz}_s = 7$ μm and $\Delta Y^{rz}_s = 87$ μm will be obtained. Thus, due to the large l_4, slight rotation of the Z axis will cause a large ΔY^{rz}_s, which should be avoided as much as possible. In order to eliminate the installation rotation error, it is necessary to install BPM with a fixed torque wrench.

EXPERIMENT AND DISCUSSION

The physical experimental platform designed according to Fig. 3 is shown in Fig. 7. To improve the calibration efficiency, the two LRSs and precision motion stages are controlled by a computer program. The parameters of the tested BPM are $H = 210$ and $L = 12$. Support parameter $H_s = 182$ and the diameter of the antenna $r = 0.105$. By completing step 1 in Table 1, we can get $X_s = 5.820$, $Y_s = 1.780$, $X_{bpm\_M} = -0.287$, and $Y_{bpm\_M} = -0.328$. The unit of all above data is mm. Then, install a BPM and

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adjust its position until the antenna is located at the electrical center, and measure X_{bpm_E} and Y_{bpm_E}. Repeat the experiment 5 times in three different ways and observe the repeatability accuracy. The experimental data is shown in Table 3.

Table 3 shows that changing only the antenna or BPM results in small random errors, and the repeatability accuracy is within 10 µm. If both of them are changed simultaneously, the repetition precision is approximately 15 µm. The more objects that are changed, the more uncertainties are introduced and the greater the measurement error is obtained. In practical engineering, each calibration requires manual operation of the BPM and antenna at the same time, so the third row in Table 3 is the most realistic. On the basis of three-sigma rule, the range of measurement results is mostly within ±30 µm.

CONCLUSION

In order to quickly, low-cost, and high-precision measure the BPM electro-mechanical offset, a new method using precision antenna support and laser ranging sensor is proposed. The system's mechanical components are designed, and an automatic measurement program was developed. The resolution and maximum absolute error of this method are 15 µm and 20 µm, respectively. Improving the machining accuracy and surface finish of the antenna support, and designing a more reliable antenna pressing mechanism can further improve the calibration accuracy.

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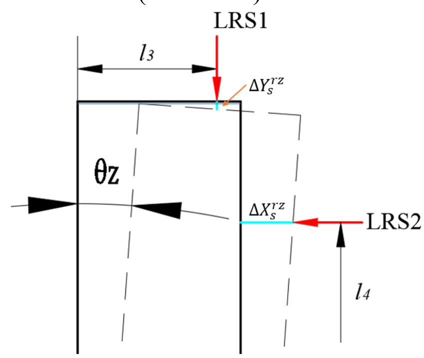

Figure 6: The error model for BPM rotation around Z-axis.

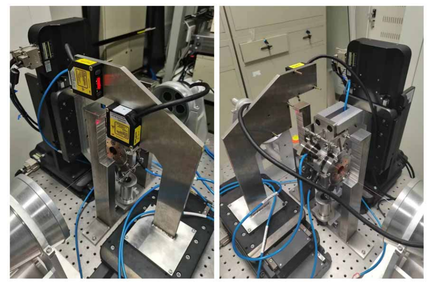

Figure 7: The experimental platform.

Table 3: The Experimental Data (unit: µm)

Measurement operation	σ_{x_offset}	σ_{y_offset}
Repeat installation of the BPM without changing the status of the antenna	3.3	10.2
Repeat installation of the antenna without changing the BPM status	8.1	2.4
Repeat the installation of the antenna and BPM simultaneously	15.4	12.2

Table 2: BPM Installation Errors Analysis

Error Source	Effect on Measurement	Elimination Method
Rotation around X-axis	$\Delta X_{bpm\_E}^{rx}$ is difficult to evaluate. $\Delta Y_{bpm\_E}^{rx}$ is difficult to evaluate. $\Delta Y_s^{rx} \approx l_1\theta_x$, l_1 is the distance from the laser spot to the X-Y plane. θ_x is the rotational error.	Hardware: Tighten the BPM mounting screws using a fixed torque wrench Software: The LRS1 scans along the Z-axis and the error ΔY_s^{rx} can be eliminated by averaging the measured Y_s at multiple positions.
Rotation around Y-axis	$\Delta X_{bpm\_E}^{ry}$ is difficult to evaluate. $\Delta Y_{bpm\_E}^{ry}$ is difficult to evaluate. $\Delta X_s^{ry} \approx l_2\theta_y$, l_2 is the distance from the laser spot to the X-Y plane. θ_y is the rotational error.	Hardware: Tighten the BPM mounting screws using a fixed torque wrench Software: The LRS2 scans along the Z-axis and the error ΔX_s^{ry} can be eliminated by averaging the measured X_s at multiple positions.
Rotation around Z-axis	$\Delta X_{bpm\_E}^{rz}$ is difficult to evaluate. $\Delta Y_{bpm\_E}^{rz}$ is difficult to evaluate. $\Delta Y_s^{rz} \approx l_3\theta_z - H\theta_z^2/2$, l_3 is the distance from the laser spot to the Y-Z plane. θ_z is the rotational error. $\Delta X_s^{rz} \approx l_4\theta_z$, l_4 is the distance from the laser spot to the X-Z plane.	Hardware: Tighten the BPM mounting screws using a fixed torque wrench No feasible software elimination method

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