

Applications of Non-contact Measurement Using Coordinate Measuring Machines in High-energy Light Sources

Authors: Han Yuanying, Dong Lan, copper oxychloride, Lu Shang, Yan Luping, Zhang Luyan, Liu Xiaoyang, Yan Haoyue, Ma Na, He Zhenqiang, Ke Zhiyong, Men Lingling, Li Bo, Wang Xiaolong, Liang Jing

Date: 2025-04-22T11:04:17+00:00

Abstract

This paper proposes a hybrid coordinate measuring system based on collaborative operation of contact and non-contact probes to address complex requirements in alignment measurement for high-energy synchrotron radiation light sources, including wire position measurement, thin blade edge monitoring, and accuracy verification of vision scanning equipment. By integrating vision probes and contact probes, the system fully leverages their complementary advantages in accuracy, efficiency, and adaptability, successfully overcoming limitations of traditional single-probe methods for easily deformable components, highly reflective surfaces, and complex geometric features. Experimental results demonstrate that in applications such as rotating wire magnetic center extraction, adjustable slit blade zero calibration, and tension wire scanner accuracy verification, the comprehensive measurement uncertainty of the hybrid system reaches as low as 6.09 μm . Specifically, the zeroing adjustment time for adjustable slit blades at beamline stations is reduced to 0.25 hours compared with traditional methods, achieving an accuracy of 10 μm and an efficiency improvement of more than fourfold. This hybrid measuring system achieves high-precision collaborative measurement, significantly enhancing efficiency and reliability of alignment operations, meeting alignment measurement requirements of high-energy light sources. It demonstrates an important development trend of coordinate measuring machine technology in light source alignment and provides technical reference for multi-probe collaborative measurement in other precision engineering fields.

Full Text

Preamble

Vol. XX, No. X, XXX 20XX

NUCLEAR TECHNIQUES

Application of Non-Contact Coordinate Measuring Machine in High-Energy Light Sources

HAN Yuanying¹, DONG Lan^{1,2}, WANG Tong^{1,2}, LU Shang¹, YAN Luping¹, ZHANG Luyan¹, LIU Xiaoyang¹, YAN Haoyue¹, MA Na^{1,2}, HE Zhenqiang^{1,2}, KE Zhiyong^{1,2}, MEN Lingling^{1,2}, LI Bo^{1,2}, WANG Xiaolong^{1,2}, LIANG Jing^{1,2}

¹ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

² Dongguan Neutron Science Center, Dongguan 523803, China

Abstract

[Background]: The high-energy synchrotron radiation light source represents one of the world's brightest fourth-generation synchrotron radiation facilities. With its extensive storage ring circumference and large quantity of magnets, the alignment measurement demands exceptionally high precision. [Purpose]: To address complex requirements in high-energy synchrotron radiation source alignment—such as wire position measurement, thin blade edge monitoring, and visual scanning equipment accuracy verification—this paper proposes a hybrid coordinate measurement system based on collaborative operation of contact and non-contact probes. [Methods]: By integrating an imaging probe with a contact probe, the system leverages their complementary advantages in accuracy, efficiency, and adaptability, successfully overcoming limitations of conventional single-probe methods when dealing with deformable components, highly reflective surfaces, and complex geometric features. [Results]: Experimental results demonstrate that the hybrid system achieves a comprehensive measurement uncertainty as low as 6.09 μm in applications including rotating wire magnetic center extraction, adjustable diaphragm blade zero calibration, and tension wire scanner accuracy verification. Notably, the blade zeroing adjustment time for beamline front-end stations was reduced to 0.25 hours with 10 μm precision—more than four times more efficient than traditional methods. [Conclusions]: The hybrid measurement system enables high-precision collaborative measurement, significantly improving alignment efficiency and reliability while meeting high-energy light source alignment requirements. This work reveals important development trends for CMM technology in light source alignment and provides technical references for multi-probe collaborative measurement in other precision engineering fields.

Keywords: CMM, Non-contact measurement, Composite measuring system,

Uncertainty

Introduction

The High Energy Photon Source (HEPS) is China's first high-energy synchrotron radiation facility and among the brightest fourth-generation synchrotron radiation sources worldwide [1]. Currently, HEPS has completed construction of its accelerator and first batch of beamlines, undergoing multiple rounds of beam commissioning and light commissioning. The storage ring spans 1,360 meters in circumference with numerous magnets, imposing stringent demands on alignment measurement precision.

The alignment system is responsible for magnetic center measurement of booster magnets. To meet magnetic center extraction calibration error requirements, a single-turn rotating coil magnetic center calibration system was developed, requiring wire position information during the process. In beamline front-end areas, adjustable diaphragms need internal blade edge position monitoring in the slit after calibration, with motor-controlled blade movement to the zero position. The storage ring control network has a long circumference; when schedules are tight, extensive manpower and instrumentation are required, resulting in low efficiency and long durations. Consequently, the alignment system is investigating tension wire methods for control network measurement, having completed one round of control network surveying in the storage ring tunnel. To achieve higher-precision tension wire tunnel measurements, a blue-light absolute scanner was procured for use with laser trackers. Prior to deployment, the scanner's line measurement accuracy required verification against other equipment while mastering its measurement methodology. Conventional laser trackers and single-probe CMMs cannot directly measure soft, easily deformable wires or thin blade edges [2], failing to meet practical HEPS alignment measurement needs. To accomplish these measurements with higher efficiency and precision, multiple measurement systems must collaborate [3]. Therefore, we procured a CMM integrating both contact and non-contact (also called imaging) measurement capabilities, where the two probe types alternate to jointly complete measurements of the same equipment or system, playing a crucial role in light source alignment work [4-5].

This paper presents a hybrid measurement system based on alternating use of CMM contact and non-contact (imaging) probes, focusing on non-contact measurement applications in high-energy light sources. The system addresses practical challenges including wire position measurement, blade edge position monitoring, and scanner wire measurement accuracy verification. By fully leveraging each probe's measurement characteristics, the system achieves complete, high-precision collaborative measurement, satisfying HEPS alignment requirements and demonstrating the necessity and practicality of the hybrid CMM system, yielding more accurate and credible results.

1. Comparison of Contact and Non-Contact Measurement Methods

CMMs have various structural configurations. The PILOT 15.30.12 model used in HEPS alignment work features a semi-gantry structure with column-type guide walls on one side, as shown in [Figure 1: see original paper]. Its measurement range is $1500 \text{ mm} \times 3000 \text{ mm} \times 1200 \text{ mm}$, with a maximum permissible indication error of $3.5 + 3.5L/1000 \text{ m}$. The data processing software is PC-DMIS, which guides the CMM through measurement by planning sampling points via probe movement. CMMs are large-range, high-precision, versatile instruments [6-8] equipped with both contact and non-contact probes, enabling two measurement approaches.

Contact measurement offers high reliability and precision. The measured component is placed on a granite platform; moving the CMM contact probe to contact the workpiece yields the stylus center's x, y, z coordinate data [9], capturing the measured feature's profile. Contact measurement is widely applied, conveniently acquiring surface information for geometric dimension inspection. However, it requires force between the probe and workpiece with point-by-point detection, stopping measurement upon contact before lifting to the next position. Contact measurement cannot precisely measure soft, easily deformable materials or thin edge positions, potentially causing slipping, friction, and elastic deformation that introduce measurement errors [10-11].

Non-contact measurement adjusts the distance between the imaging probe and workpiece to clearly present image edges, offering advantages of speed and avoiding workpiece contact. It can measure soft and deformable materials, fragile components, and inaccessible areas. However, its measurement accuracy is inferior to contact measurement and is significantly affected by surface characteristics such as brightness, color, and roughness [12-13]. HEPS alignment work—including rotating wire magnet measurement, front-end equipment calibration, scanner accuracy verification for tension wire control networks, and vibrating wire displacement gauge calibration—employs combined methods: imaging probes measure wires and thin blade edges while contact probes measure solid spheres and reference surfaces. Non-contact measurement plays a vital role in alignment work, with different CMM probe types alternating to complete measurements collaboratively, representing an important trend for CMM technology in accelerator alignment.

2. Non-Contact Measurement Principle

Non-contact measurement technology is based on optical imaging and digital image processing, efficiently acquiring spatial coordinates by capturing optical signals from measured object surface features. Compared with traditional contact measurement, this method avoids deformation errors caused by mechanical contact, making it particularly suitable for precision inspection of flexible materials, highly reflective surfaces, and microstructures. In HEPS alignment work,

three-dimensional positioning of wires and profile extraction of thin sheet workpieces are critical measurement requirements, with imaging probes becoming key technical tools due to their non-invasive nature and rapid imaging capability.

2.1 Imaging Probe for Wire Measurement

Rotating wire, tension wire, and vibrating wire experiments all require wires for measurement, necessitating wire position and sag information. Therefore, studying non-contact wire measurement methods to improve accuracy and reliability, combined with contact probe collaboration, enables complete high-precision measurement. Imaging probes can only perform accurate planar two-dimensional measurement; height values perpendicular to the probe direction are measured inaccurately. Thus, to obtain three-dimensional wire position information for sag calculation, two-dimensional measurements must be transformed into three-dimensional through coordinate integration calculations.

The CMM's elevation direction corresponds to its mechanical coordinate system's Z-axis, with the XY plane parallel to the granite platform. When the wire ends are tensioned as shown in Figure 2: see original paper, the wire parallels the coordinate system's Y-axis. The imaging probe measures vertically downward, producing a two-dimensional image as shown in [Figure 3: see original paper], where the black elongated portion represents the wire and the black-white boundary represents the wire edge. Due to material and tension effects, wire reflectivity and tensioned diameter vary, making the black strip width inconsistent in images. Therefore, imaging probe wire measurement must determine the wire's axial position.

When the imaging probe measures vertically downward perpendicular to the granite plane, the obtained elevation coordinate value z_1 for that wire segment is inaccurate and unreliable; this elevation value should be disregarded. The wire image obtained is shown in [Figure 3: see original paper]. Clicking with the mouse on the wire image's left edge selects two points to obtain the left edge line; similarly, the right edge line is obtained. Constructing the bisector of the left and right edge lines yields the wire axis, represented by the axis midpoint coordinates (x_1, y_1, z_1) . Since imaging probes only enable two-dimensional measurement within the vertical plane, the axis midpoint's effective two-dimensional coordinates are (x_1, y_1) , with the elevation coordinate discarded. To achieve three-dimensional wire measurement, the imaging probe must be rotated horizontally as shown in Figure 2: see original paper, making the probe parallel to the X-axis and perpendicular to the YZ plane, with elevation direction as the X-axis. Horizontal measurement yields wire axis coordinates (x_2, y_2, z_2) , with effective two-dimensional coordinates (y_2, z_2) . To ensure measurement of the same wire segment, the difference between y_1 and y_2 must be minimized; in practice, this difference is controlled within 10 μm . The horizontal probe measurement method yields accurate z_2 coordinate values for that axis segment, which integrate with vertical measurement coordinates to obtain the three-dimensional wire axis coordinates (x_1, y_1, z_2) .

2.2 Imaging Probe for Thin Sheet Measurement

HEPS thin sheet components such as sextupole iron laminations, shown in [Figure 4: see original paper], require profile acquisition to assess machining quality. Adjustable diaphragms require blade edge position acquisition on the slit side to facilitate zero adjustment via motor control systems. Stylus probes cannot detect thin sheet edges, potentially causing measurement errors from probe jumping and slipping. Therefore, imaging probes are needed for profile acquisition in inaccessible situations. First, the workpiece surface is cleaned and placed on the CMM table. The imaging probe moves in the plane perpendicular to the measured profile, stopping at fixed points for measurement to obtain sampling point coordinates on the workpiece. The metal sheet's contour image is shown in [Figure 5: see original paper], where the metal surface appears as bright textured patterns and the edge line at the dark-bright boundary represents the workpiece contour edge. For metal sheet workpieces, probe brightness should be maximized to enhance contrast between dark and bright regions, obtaining clear boundary contour images.

3. Non-Contact Measurement Applications in High-Energy Light Sources

As alignment measurement methodologies advance, CMMs with single probes can no longer meet certain measurement requirements, necessitating hybrid CMM systems with alternating contact and non-contact probes. Through joint calibration of imaging and contact probes to unify coordinate systems, the system ensures precision consistency and coordination between different measurement principles, enhancing overall system reliability to meet diverse experimental measurement needs.

3.1 Rotating Wire Magnetic Center Extraction

To ensure magnetic center pre-alignment precision for HEPS magnets, the alignment system designed a unique single-turn rotating coil magnetic center calibration system, shown in [Figure 6: see original paper]. The traditional multi-turn compensation coil is simplified into two connectable windings: one wire serves as the rotation axis, achieving four-axis collinearity with the magnet's mechanical center and both rotary tables' rotation centers; the other wire is the revolution axis for rotating through magnetic flux lines, with the distance between the two wires representing the rotation radius. The rotating coil system principle involves calibrating to obtain the magnet's mechanical center, then measuring the deviation between magnetic and mechanical centers using the rotating coil, finally establishing a coordinate system with the magnetic center as origin to extract the magnetic center to four reference points on the magnet top. The measurement coil uses 0.125 mm diameter beryllium-copper alloy wire composed of over 98% copper (Cu) and 1.8%-2.0% beryllium (Be), with tensile strength of approximately 1105 MPa and elastic modulus of 128 GPa, renowned for high

strength, good wear resistance, corrosion resistance, and excellent conductivity.

Magnetic center calibration comprises three main steps. First, the CMM contact probe measures the magnet's pole faces and reference planes to establish a calibration coordinate system, identifying the mechanical center and extracting it to four reference points on the magnet top. Second, the imaging probe scans wires near both magnet ends, measuring from vertical and horizontal directions. After data integration, the axis position of the single-side wire segment is obtained, represented by three-dimensional coordinates of the axis midpoint. The line L connecting two axis midpoints represents the wire position passing through the magnet. By fitting the magnet's inlet-outlet connection line parallel to the beam direction to the wire position, the deviation between coil axis and magnet beam flow can be determined through the magnet top reference point coordinates. This deviation can be adjusted via the magnet bottom adjustment mechanism to align the wire axis with the magnet mechanical center. Finally, driving high-precision synchronous rotary tables at constant angular velocity rotates the wire through magnetic flux lines, generating induced voltage varying with the magnetic field. Processing and analyzing the voltage signals and rotation angles yields the deviation between magnetic and mechanical centers, achieving magnetic center position measurement.

Non-contact measurement applications in the rotating wire magnetic center measurement system manifest in three aspects: (1) During rotating wire mechanism construction, achieving collinearity between both rotary tables' rotation centers and the wire. The method involves using the imaging probe to perform three-dimensional scanning measurement on the wire segment near each rotary table following Section 2.1's method, then rotating the tables multiple times through 360° total. Spherical nests on the back panels can adsorb 0.875-inch high-precision solid spheres, whose positions are measured by the contact probe at each rotary table angle. Multiple sphere center positions are fitted into a circle to obtain the rotary table's rotation center. Based on measured data, whether the wire axis and rotary table rotation center are collinear can be determined; if not, adjustment via the back-panel structure achieves three-axis collinearity between the wire and both rotary table rotation centers. (2) Using the imaging probe for three-dimensional scanning of wires at both magnet ends, adjusting the magnet mechanical center to be collinear with the wire position, ultimately achieving four-axis collinearity among the wire, both rotary table rotation centers, and the magnet mechanical center. (3) Performing three-dimensional scanning measurement across the entire wire in segments to obtain multiple wire segment axis position coordinates. Fitting multiple point coordinate values into a curve via least squares method enables wire sag analysis.

3.2 Front-End Equipment Calibration

The beamline front-end area contains multiple structurally similar but not identical monochromatic adjustable diaphragms, with apertures defined by four independently moving blades, as shown in [Figure 7: see original paper]. The

left side has upper and lower blades, the right side has left and right blades. The blades' primary functions are obtaining specific spot sizes and clear spots while blocking stray light. Diaphragm calibration requires moving blades to the zero position via control software, with the blade travel zero position on the beam center. The traditional method first uses a laser tracker to calibrate and find the equipment' s mechanical center (collinear with the beam center), then combines this with the beam center position found by the laser tracker, using a tool theodolite to aim at blade edges for movement to the travel zero position—a process requiring at least 3 hours with uncertain adjustment precision.

Currently, high-precision hybrid CMMs complete diaphragm calibration and blade zero adjustment as follows: (1) The CMM contact probe measures the equipment's left/right end faces, top face, and four alignment reference points, as shown in Figure 8: see original paper. The measured reference planes establish a mechanical center coordinate system with origin on the beamline, transverse as X-axis, elevation as Y-axis, and beam direction as Z-axis. (2) Switching to the imaging probe for horizontal measurement of blades at one end, as shown in Figure 8: see original paper. Probe light intensity is adjusted above 90% to clearly display blade edge images in software, as shown in [Figure 9: see original paper]. For upper/lower blades to move to the beam center position (blade edge line passing through equipment mechanical center), the elevation Y coordinate value of any point on the edge should be 0. In practice, blades are not at zero but at arbitrary travel positions. Adjusting the working distance between probe and blade presents clear blade edge images in software. Clicking any point on the edge line yields the edge point coordinates, where the Y coordinate value represents the blade' s elevation deviation from the beam center. Similarly, the X coordinate value of left/right blade edge points represents the blade' s transverse deviation from the beam center. Based on measured deviations, motors are controlled to move blades to the beam center position. After repositioning, blades are remeasured to verify adjustment, and the travel zero position is set in the diaphragm motor control software. Imaging probe-based diaphragm blade adjustment achieves precision within 10 μm in approximately 0.25 hours, dramatically improving efficiency.

3.3 3D Scanning Equipment Accuracy Verification

Tension wire measurements for control networks were conducted in the HEPS storage ring tunnel. The alignment system aims to deeply investigate this method to address the low efficiency of laser tracker measurements for large-scale control networks. Tension wires' physical properties enable extremely high-precision distance measurement with strong anti-interference capability and long-term stability, crucial for alignment and positioning of key components (magnets, vacuum chambers) in particle accelerators [14]. Consequently, the alignment system procured a blue-light absolute scanner for use with laser trackers in tunnel tension wire measurements. To verify the scanner' s line measurement accuracy, a scanner wire absolute accuracy verification system was

built on the CMM granite platform, as shown in [Figure 10: see original paper]. The wire ends are tensioned by a mechanism, with one target seat attached beside the wire's middle section and four target seats attached on the surrounding granite platform for placing 1.5-inch high-precision solid spheres or tracker targets.

Blue-light absolute scanner line accuracy experimental steps: (1) The scanner measures the wire while the laser tracker measures targets, obtaining wire position and five sphere center positions. (2) In scanner software, spheres 1-4 centers construct a plane, projecting the wire and sphere 5 onto the plane to calculate the two-dimensional distance D1 between wire axis and sphere 5 center for comparison with CMM results.

CMM line accuracy experimental steps: (1) The contact probe measures spheres 1-4 to obtain solid sphere center coordinates and fit a plane. (2) The imaging probe measures the wire vertically downward in segments to obtain each segment's axis, fitting axis segments into a straight line to participate in coordinate system establishment. (3) Using the plane's normal direction as Y-axis, the line as Z-axis, and sphere 5 center as origin, the two-dimensional distance D2 between the line and sphere 5 center along the X-axis is compared with distance D1.

Experimental results show the difference between D1 and D2 is 0.02 mm, indicating the scanner's line measurement reliability for control network tension wire measurement. Close-range photogrammetry can also achieve wire measurement. A photogrammetric wire accuracy verification system was built on the granite platform, as shown in [Figure 11: see original paper], using the same method as the scanner line accuracy verification experiment to validate photogrammetric wire accuracy [15].

4. Uncertainty Analysis of Multi-Probe Hybrid Measurement System

- (1) According to the CMM imaging probe specifications, its comprehensive measurement error within the field of view is 4 μm , representing the uncertainty component introduced by the imaging probe: $u_1 = 4 \mu\text{m}$. According to contact probe specifications, the maximum indication error within 1 meter is 3.5 μm , so the uncertainty component introduced by the contact probe is taken as $u_2 = 3.5 \mu\text{m}$. During hybrid measurement, contact and imaging probes alternate, so the combined uncertainty component from both probes is: $u_3 = \sqrt{(u_1^2 + u_2^2)} = 5.3 \mu\text{m}$.
- (2) HEPS has calibrated numerous magnets using CMM, with each magnet undergoing two calibration measurements to obtain two sets of alignment reference point coordinate values. The difference D between the two calibration values represents the magnet's measurement repeatability precision. Statistics from hundreds of magnets undergoing two CMM calibrations show the standard deviation of reference point differences D is 3 μm ,

so the uncertainty component from measurement repeatability is: $u_4 = 3$ m.

- (3) Although the current CMM has temperature compensation, the measurement environment temperature of 25°C differs from the standard 20°C temperature, but its impact on measurement results is negligible: $u_5 = 0$ m.

Through analysis of uncertainty error sources, uncertainty components under various influencing factors were obtained. Since no significant correlation exists between components, the combined standard uncertainty is: $u_c = \sqrt{(u_3^2 + u_4^2 + u_5^2)} = 6.09$ m.

This paper systematically introduces the comprehensive application of CMM non-contact measurement technology in HEPS alignment measurement work. By integrating a hybrid measurement system with contact and non-contact probes, the system effectively resolves precision and efficiency bottlenecks of traditional methods in flexible components, thin sheet edges, and complex scenarios, meeting alignment measurement requirements. Research shows: (1) Imaging probes demonstrate significant advantages in rotating wire magnetic center measurement and beamline equipment calibration, achieving three-dimensional wire positioning and thin sheet profile extraction. Combined with contact probe high-precision characteristics, collaborative measurement of systems containing multiple component types is completed. In adjustable diaphragm blade zeroing adjustment, imaging probes reduced adjustment time to 0.25 hours with 10 m precision—over four times more efficient than traditional methods. (2) For blue-light scanner tension wire precision measurement experiments, CMM achieved wire axis deviation analysis through alternating contact and imaging probe measurements. Verification results show only 0.02 mm deviation between scanner and CMM measurements, with the CMM system's combined standard uncertainty at 6.09 m, meeting HEPS' s stringent sub-millimeter precision requirements. CMM imaging probe wire measurement demonstrates high precision and reliability. This method of establishing coordinate systems using wires and examining wire-sphere distances to verify other equipment' s line measurement accuracy merits reference; in practice, this method also verified laser radar scanner and photogrammetric line measurement accuracy.

Future research must further optimize imaging probe adaptability to object surface characteristics (reflectivity, roughness) to enhance non-contact measurement reliability in complex engineering environments and continue exploring multi-probe collaborative measurement applications. This study validates the hybrid measurement system' s practicality and reliability in large scientific facility alignment engineering, providing important references for measurement technology in high-energy light sources and other precision engineering fields.

References

1. Han Yuanying, Dong Lan, Wang Tong, et al. Three coordinate calibration technique of magnet for High Energy light source [J]. High Power Laser and Particle Beams, 2024, 36(09): 64-69.
2. Zhang Hongyan. Research on measurement system of size, Form and Position error and thread of rotary parts [D]. Tianjin University, 2014.
3. Ye Xiuling. Research on Key technology of multi-probe cooperative measurement of compound coordinate measuring machine [D]. Tianjin university, 2018. DOI: 10.27356/d.cnki.gtjdu.2018.000755.
4. Hu Jianfeng. Research on Coordinate Measurement and Data Processing of Automobile Body [D]. Hunan University, 2011.
5. Zhang Wangxian, Zhong Sidong, Sui Libin, et al. Large size non-contact measurement based on CMM [J]. Journal of Wuhan University (Engineering and Technology Edition), 2004, (05): 112-115.
6. Zhang Zuxun, Zheng Shunyi, Wang Xiaonan. Development and application of Industrial photogrammetry [J]. Journal of Geodesy and Cartography, 2022, 51(06): 843-853. (in Chinese)
7. Qu Liyuan. Aviation blade non-contact scanning software development and sampling algorithm design [D]. Huazhong university of science and technology, 2020. DOI: 10.27157/d.cnki.ghzku.2020.004164.
8. Zhang Wangxian, Zhong Sidong, Sui Libin, et al. Large size non-contact measurement based on CMM [J]. Journal of Wuhan University (Engineering and Technology Edition), 2004, (05): 112-115.
9. Zhang Zhongbo, Wang Kai, Ma Yao, et al. Based on image measurement of small module gear parameter reverse [J]. Modern manufacturing engineering, 2018, (08): 134-138+35. DOI: 10.16731/j.cnki.1671-3133.2018.08.025.
10. Gao Jikun, Yan Feng, Li Ji. Three coordinates measuring machine in the application of whole semal blade profile detection [J]. Aviation manufacturing technology, 2015, (22): 94-97. DOI: 10.16080/j.issn1671-833x.2015.22.094.
11. Deng Xueman, Liao Junbi, Gao Zhongyou, et al. Application of non-contact measurement of CMM in Screw Measurement [J]. China Test Technology, 2006, (01): 56-58.
12. Sun Junqi. Research on error influencing factors and correction countermeasures of image measuring instrument [J]. Science and Technology Innovation, 2019, (09): 53-54.
13. Fei Yetai, Zhao Jing, Wang Hongtao, et al. Three coordinate measuring machine dynamic error analysis [J]. Journal of instruments and meters, 2004, (S1): 773-776. DOI: 10.19650/j.cnki.cjsi.2004.s1.330.

14. Yuan Jiandong. Application of tensioning technology in accelerator collimation measurement [J]. High Power Laser and Particle Beams, 2020, 32(04): 22-31.
15. Liang Jing, Dong Lan, Wang Tong, et al. Application of close-range photogrammetry in particle accelerator collimation [J]. High Power Laser and Particle Beams, 2019, 31(03): 73-77. (in Chinese)

Author Contributions

Han Yuanying was responsible for research design, data measurement and processing, and drafting and revising the final manuscript. Dong Lan was responsible for research conception and design, supervision, and guidance. All other authors supervised the research and provided improvement suggestions.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.