Research Progress and Prospects of Particle Accelerator Alignment Technology

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Abstract

As a fundamental guarantee for the performance of large-scale scientific facilities, particle accelerator alignment technology aims to achieve high-precision spatial positioning of key components such as magnets. The advancement of alignment precision from the sub-millimeter level to sub-micron and even nanometer scales has become crucial for the development of high-energy physics, synchrotron radiation light sources, and free-electron lasers. This paper focuses on the particle accelerator alignment technology system, introducing core instruments and techniques throughout the entire process at the measurement methodology level, including control network optimization, component pre-alignment, installation smoothing, and deformation monitoring. This paper systematically summarizes the independently innovative technical system developed in China during the 12th to 14th Five-Year Plan periods through major scientific research projects such as the High Energy Photon Source (HEPS), Shanghai High-repetition-rate XFEL and Extreme Light Facility (SHINE), High Intensity heavy-ion Accelerator Facility (HIAF), and Hefei Advanced Light Facility (HALF), including achievements such as four-beam laser pre-alignment technology, multi-sensor data fusion technology, and control network design and optimization technology. This paper also provides an in-depth analysis of the numerous challenges faced by future accelerators such as the Circular Electron Positron Collider (CEPC), specifically including multi-physics field coupling measurement difficulties, challenges in high-precision in-situ particle accelerator component monitoring, technical bottlenecks in uncertainty expression and standardization for the entire alignment process, and issues regarding how to fully utilize artificial intelligence empowerment and achieve automated alignment. This paper provides an outlook on the development prospects of particle accelerator alignment technology, offering insights for researchers in this field.

Full Text

Preamble

Research Progress and Prospects of Particle Accelerator Alignment Technology

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Abstract

Particle accelerator alignment technology serves as a fundamental guarantee for the performance of large-scale scientific facilities, with its core objective being the high-precision spatial positioning of critical components such as magnets and RF cavities. The alignment precision has advanced from the sub-millimeter level to sub-micrometer and even nanometer scales, becoming a pivotal factor in the development of high-energy physics, synchrotron radiation light sources, and free-electron lasers. This paper focuses on the alignment technology system for particle accelerators, introducing core instruments and techniques across the entire workflow—including control network optimization, component pre-alignment, installation smoothing, and deformation monitoring. We systematically summarize the innovative alignment technology system independently developed in China during the 12th to 14th Five-Year Plan periods through major scientific projects such as the High Energy Photon Source (HEPS), Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE), High Intensity Heavy-Ion Accelerator Facility (HIAF), and Hefei Advanced Light Facility (HALF). These achievements include four-laser pre-alignment technology, multi-sensor data fusion techniques, and control network design and optimization methodologies. The paper also analyzes key challenges facing future accelerators like the Circular Electron Positron Collider (CEPC), including multi-physics coupled measurement complexities, high-precision in-situ monitoring of accelerator components, uncertainty expression and standardization bottlenecks throughout the alignment process, and the integration of artificial intelligence for automated alignment. We conclude by outlining future development prospects for particle accelerator alignment technology to provide insights for researchers in this field.

Keywords: Particle Accelerator Alignment, Data Fusion, Control Network, Uncertainty, Artificial Intelligence

1. Introduction to Particle Accelerator Alignment Technology

Particle accelerator alignment is the process of installing all in-vacuum equipment—including magnets, accelerating tubes, and vacuum systems—at designated positions with specified precision according to accelerator physics design requirements. This technology provides geometrically smooth beam orbits from a spatial perspective and conducts long-term deformation monitoring during accelerator operation to ensure stable light source performance [14]. As shown in

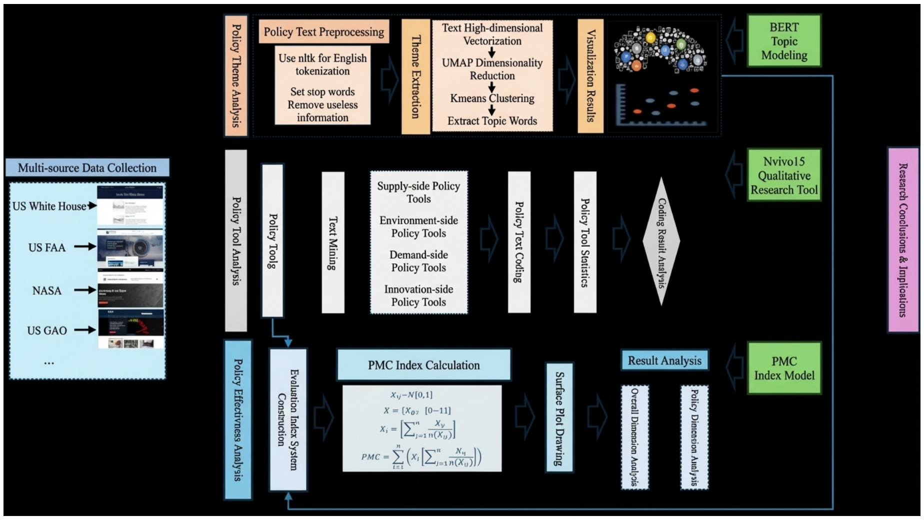

Figure 1: Figure 1

, alignment measurement work involves rational error allocation across various engineering stages, specifically including component calibration and pre-alignment, control network deployment and measurement, on-site installation and rough alignment, smoothing and fine alignment, and deformation monitoring [15-20].

Alignment measurement for particle accelerators represents a branch of precision engineering surveying, aiming to achieve metrological-level precision under large-scale engineering measurement benchmarks [4]. In the particle accelerator domain, measurement precision requirements for components such as magnets typically reach sub-millimeter levels or even tens of micrometers [21]. As illustrated in

, global large-scale scientific facility construction has accelerated, with over 100,000 users currently working at more than 50 synchrotron radiation facilities worldwide. lists the alignment accuracy requirements for major international synchrotron radiation sources. Taking HEPS and HALF as examples, the precision requirements for magnet-to-magnet and girder-to-girder alignment have reached 30 m and 50 m, respectively [12,22]. To meet these demanding engineering requirements, the field must continuously develop novel instruments, advance traditional data processing methods and theories, and improve existing measurement techniques and implementation schemes.

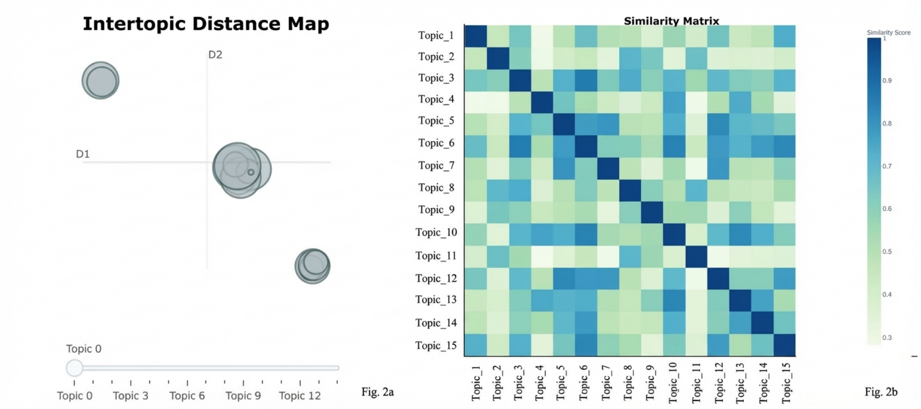

Figure 2: Figure 2

2. Progress in Particle Accelerator Alignment Instruments

Driven by the growing demands of large-scale projects such as the Future Circular Collider (FCC), Circular Electron Positron Collider (CEPC), and Compact Linear Collider (CLIC), particle accelerator alignment has increasingly employed diverse key instruments and cutting-edge measurement devices, including measurement arms, structured light systems, distributed fiber optic sensors, photogrammetry systems, hydrostatic leveling systems, laser scanners, total stations, and laser trackers. As these technologies continue evolving, we are advancing toward greater precision and efficiency, providing solid technical support for future particle accelerator projects. Below is a brief overview of frontier developments in selected alignment instruments.

2.1 Laser Tracker

Since its invention, extensive research in surveying, metrology, and mechanical engineering has propelled the development of the laser tracker, establishing it as a key measurement device in large-scale dimensional metrology. Laser trackers offer low measurement uncertainty across large ranges, automatic laser capture of spherical reflectors even during movement, high data acquisition rates, and excellent portability, making them core tools for achieving stringent alignment precision in particle accelerators [21].

shows major domestic and international laser tracker manufacturers.

Scholars have detailed the use and applicability of laser trackers in various precision positioning activities for particle accelerators [21]. Research on laser tracker applications spans hardware design to system integration, with several critical issues requiring in-depth investigation. First is the design of measurement networks for laser trackers and measured objects in scenarios such as pre-alignment and tunnel control network measurement [6,11]. Laser trackers

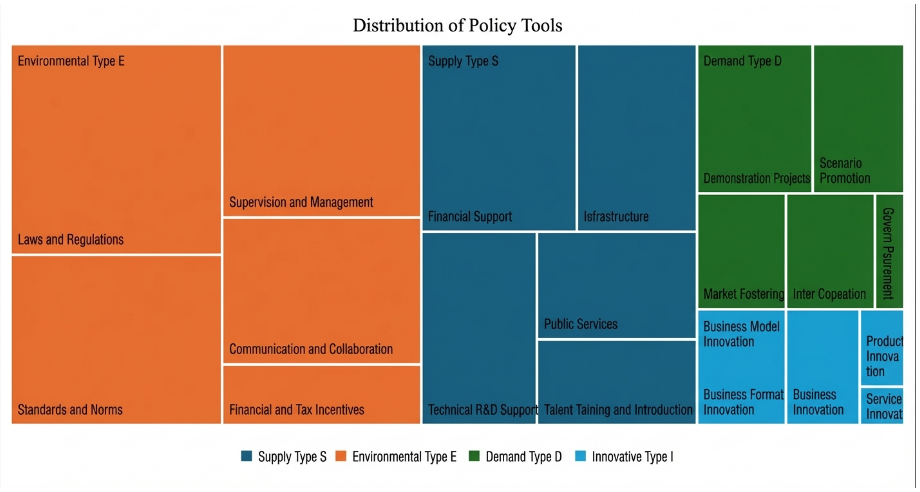

Figure 3: Figure 4

typically require simultaneous measurement of multiple accelerator components across large ranges, and in critical locations like collision regions, must maintain measurement stability under extreme conditions such as high radiation. Rational measurement network design is crucial to maximize coverage of different measurement areas while optimizing measurement precision. Second is the research focus on data fusion between laser trackers and other complex precision measurement techniques or systems [9]. A key limitation of laser trackers is difficulty maintaining stable precision across large ranges or in complex environments, which can be addressed by integrating them with advanced measurement devices such as hydrostatic leveling systems, structured light systems, and distributed fiber optic sensors to further reduce measurement uncertainty and enhance system reliability. Third is the expression of laser tracker precision and the establishment of adjustment models [30,31]. Laser tracker measurement accuracy is influenced by multiple factors, and research must address how to correct data and compensate for errors through adjustment models when different error types are present. In-depth investigation of precision expression methods and adjustment approaches can effectively improve measurement data reliability and reduce the impact of random and systematic errors on final results. Fourth is measurement accuracy evaluation and error compensation under multi-physics coupled conditions. In particle accelerator environments, measurement systems must consider not only conventional spatial positioning accuracy but also the effects of temperature variations, mechanical vibrations, electromagnetic interference, and other physical fields [1]. Multi-physics coupling effects often introduce nonlinear errors that affect measurement accuracy [32]. Therefore, investigating laser tracker measurement precision under multi-physics coupled conditions represents a long-term research direction in particle accelerator precision measurement.

2.2 Hydrostatic Leveling System

The Hydrostatic Leveling System (HLS) is a precision instrument for measuring height differences and their variations, primarily used for monitoring vertical displacement and tilt in nuclear power plants, foundation pits, and tunnels. As shown in [FIGURE:5], the measurement principle is based on the equal liquid level height in connected containers, measuring vertical height differences relative to different reference points [33].

Internationally, HLS systems have been installed in particle accelerators for real-time level monitoring of critical components such as magnets. Professor He Xiaoye’ s team at the University of Science and Technology of China pioneered systematic research on HLS hardware/software development and accuracy evaluation in China, with successful implementation in the Beijing Electron-Positron Collider Phase II, Shanghai Synchrotron Radiation Facility, and Hefei Light Source upgrade projects [34,35]. Current research priorities for HLS in particle accelerator alignment include reference height difference measurement, methods for providing elevation constraints to control network adjustment, and real-time automated deformation monitoring through multi-sensor integration [36,37].

2.3 Frequency Scanning Interferometry

As shown in [FIGURE:7], Frequency Scanning Interferometry (FSI) is a high-precision optical measurement technique widely used for measuring minute displacements. Based on laser interference principles, FSI precisely measures displacement by comparing reflected signals at different frequencies. The technology enables real-time dynamic measurement, making it suitable for moving objects [38]. In particle accelerators, FSI is used to accurately measure minute displacements of magnets and other critical components, ensuring high-precision alignment and avoiding performance deviations caused by small displacements. The compact nature of FSI systems allows deployment in confined spaces, making them suitable for extreme environment monitoring. In the ATLAS detector, automation enables FSI systems to simultaneously measure hundreds of points, revealing micrometer-level motions related to environmental changes [39]. At CERN, FSI technology monitors positions of cryogenic components and other critical elements [40]. Future circular collider detectors have achieved 1 m sensor precision and less than 5 m 3D coordinate accuracy using FSI technology, significantly enhancing alignment monitoring precision for key accelerator components [41]. Despite significant progress in measurement accuracy, environmental factors still challenge measurement stability. Therefore, the domestic particle accelerator alignment field should advance FSI technology localization and seek further breakthroughs in precision and reliability for future applications.

2.4 Laser Alignment

Laser alignment technology was applied early in accelerator domains, with Stanford University’ s two-mile linear accelerator being the first system to use laser alignment for equipment displacement monitoring [42]. This system employed rectangular Fresnel zone plates on measured targets; when laser waves illuminated the zone plates, they generated Fresnel diffraction waves on reference plates. By comparing the diffraction wave center with reference plate center points, displacement deviations were calculated with a monitoring error of 200 m. The European X-ray facility used a Poisson spot monitoring-based laser alignment system with 200 m precision. The Japanese High Energy Accelerator Research Organization employed a PSD four-quadrant sensor-based system with 60 m precision [43,44]. Internationally, ETH Zurich is actively developing, designing, evaluating, and integrating a structured laser beam-based precise alignment system for particle accelerators [45]. As shown in [FIGURE:8], domestic researchers have proposed a high-precision online alignment monitoring system based on laser beam spot similarity measurement, monitoring transverse position offsets by measuring laser imaging spot displacement. A 40-meter prototype system was built using similarity measurement algorithms to obtain relative position deviations of measured targets at different monitoring positions at different times. Testing demonstrated transverse monitoring precision better than 8 m, independent of target distance [46]. This prototype provides foundational data for developing longer-range micro-displacement monitoring systems. Future laser alignment development must continue to improve precision, stability, and automation.

2.5 Photogrammetry and 3D Reconstruction Technology

In recent years, Close-Range Photogrammetry (CRP) systems have been widely applied in particle accelerator alignment due to their high precision, non-contact nature, high efficiency, and good environmental adaptability, becoming an important means for large-scale precision measurement. As shown in [FIGURE:9], the fundamental principle of photogrammetry involves calculating the shape, size, and position of photographed objects through optical triangulation from multiple images taken at different positions [47].

Internationally, CERN’ s alignment team used Nikon D3X cameras to measure wire offset, improving radial alignment efficiency for accelerator components and effectively addressing complex environment challenges in high-luminosity hadron colliders [48]. GSI in Darmstadt plans to use photogrammetry to establish reference systems and measure hidden magnets in high-radiation areas [49]. DESY’ s PETRA IV team employs Nikon D700 cameras with V-STARS software for alignment and calibration [50]. Domestically, the University of Science and Technology of China researched and evaluated geometric measurement methods and accuracy of CRP systems, utilizing laser interferometers, laser trackers, standard tetrahedron test points, and attempting 3D reconstruction for coordinate, distance, and flatness measurement precision and repeatability

[47]. Lanzhou employs binocular cameras, leveraging non-contact measurement and equipment portability advantages to apply CRP to patient positioning and target monitoring in heavy ion therapy and magnetic measurement systems [51]. The alignment team at the Institute of High Energy Physics, Chinese Academy of Sciences, designed ten-point coded targets and pentahedral targets, conducting research on tunnel control network photogrammetry systems based on length-constrained references [52] and experimental studies on visual measuring instruments integrating photogrammetry and rangefinder functions, demonstrating high innovation and large-scale metrology application potential. As 3D scanning technology precision continues improving, 3D reconstruction techniques built from photogrammetry, laser scanning, and structured light can obtain high-density point cloud data without physical targets, enabling high-precision representation of measured object surface morphology. Compared to traditional target-based measurement, these technologies offer significant advantages in data comprehensiveness, spatial coverage, and non-contact characteristics. To further improve modeling precision and engineering efficiency in particle accelerator alignment, we recommend systematically introducing 3D reconstruction technology into the geometric modeling workflow for key accelerator components to provide data support for subsequent high-precision alignment, deformation monitoring, and error compensation.

3. Technical Progress in Key Alignment Processes

3.1 Control Network Design and Measurement Technology

Control network design and measurement technology represents a critical 环节 in particle accelerator alignment [21]. To ensure high-precision alignment of large accelerator components, the primary task for alignment teams is deploying control network points within tunnels to provide a unified reference coordinate system for all equipment installation and displacement monitoring. As the starting point of the error chain, control network design and deployment quality decisively impacts overall alignment precision. Current particle accelerator tunnel control networks have evolved from traditional geodetic surveys to integrated high-precision measurement systems incorporating multi-sensor approaches, including laser trackers, levels, photogrammetry systems, GNSS, and structured light scanning. Laser trackers, as core equipment in precision engineering measurement, have been widely applied in control network measurement for large accelerator projects due to their combination of high precision and large measurement range.

Domestic and international particle accelerator facilities have successively established tunnel control networks based on laser trackers [12,22-28,55-57]. Practitioners primarily employ SpatialAnalyzer (SA), a 3D industrial measurement software from New River Kinematics, to meet instrument interaction and collaboration requirements [58,59].

While laser trackers are the main instruments for data acquisition in accelerator alignment control networks, data processing methods and accuracy indicators vary significantly. Data processing approaches include 2D adjustment (planar and elevation) and 3D adjustment, with different computational reference planes selected and observations reduced accordingly based on network scale. These divergent approaches have led to various alignment control network adjustment software packages validated through engineering practice, including Star Net from Micro Survey [25], PANDA from GEOTEC [60], LGC developed by CERN [61], NETOBS from Michigan State University [62], and VECTOR from the Institute of High Energy Physics, Chinese Academy of Sciences [63]. These software systems continuously optimize processing accuracy, data collaboration, and residual evaluation to support complex tunnel control network data processing.

Common control network accuracy indicators include post-adjustment unit weight error, coordinate cofactor matrices, coordinate standard errors, point position errors, coordinate difference cofactor matrices, and SA-provided error (SA-E) and uncertainty (SA-U) values. [FIGURE:11] lists accuracy indicators for major international particle accelerator tunnel control networks. Early international control network data processing was evaluated within adjustment systems, later evolving primarily to SA data processing. Facilities such as Sirius, SOLEIL-II, KEK e-/e+ injector, and EBS primarily use SA-provided uncertainty [24,26,64], while NSLS-II, MAX-IV, and Diamond mainly use SA-provided error [25,54,57]. Therefore, in-depth research is needed on the selection of control network accuracy indicators.

Looking ahead, control network technology development should further deepen research at the hardware-software collaboration level. On one hand, more robust instrument collaborative measurement systems must be constructed to achieve efficient data fusion between laser trackers, hydrostatic levels, photogrammetry systems, and other multi-source instruments. On the other hand, unified standardization of alignment adjustment models should be promoted, combining uncertainty propagation theory and Monte Carlo methods to establish complete error modeling and accuracy control systems. Additionally, international collaboration is needed to standardize laser tracker error expression methods to enhance interoperability and comparability of global particle accelerator control network data processing. The ultimate goal is to construct a unified paradigm covering the entire process from control network design, measurement, and processing to evaluation, providing solid spatial reference support for future large-scale alignment projects in high-energy accelerators.

3.2 Accelerator Component Calibration and Pre-Alignment Technology

Component calibration accuracy has always been a central concern in particle accelerator alignment. To achieve high-precision component calibration and alignment, major international research institutions have conducted extensive key technology research. ESRF employs laser trackers combined with stretched wire technology to achieve high-precision 3D coordinate measurement of magnet surface reference points on dedicated measurement platforms, using the Guide to the Expression of Uncertainty in Measurement (GUM) to establish calibration error models for uncertainty analysis [24]. APS uses rotating wire platforms for magnet fiducialization and employs Hall probes for dipole magnet field measurement [65]. HEPS calibrates magnet mechanical centers using Coordinate Measuring Machines (CMM) and corrects pole gap deviations by rotating the calibration coordinate system to effectively reduce main field skew components [66,67]. CERN’ s PACMAN project determines magnet fiducial points based on stretched wire methods combined with CMM and micro-triangulation [68]. NSLS-II systematically analyzed error sources between mechanical and magnetic centers, identifying reference hole looseness, temperature variations, and measurement methods as primary error factors, while HEPS has also achieved high-precision correlation between insertion device magnetic centers and external references [69]. SPring-8-II employs vibrating wire methods to avoid traditional mechanical reference deviations, representing a key technology for magnet alignment [70].

Pre-alignment encompasses the measurement and determination of centerline alignment and relative positional relationships among components within magnet units, as well as the establishment and measurement of unit alignment references. These references enable precise adjustment of each component to its theoretical coordinates during installation [71].

The ESRF-EBS project achieved high-precision alignment through laser trackers, stretched wire methods, and girder plane control. CLIC utilized support pre-alignment networks and metrology reference networks 协同, employing stretched wire sensors and hydrostatic level sensors to achieve radial alignment RMS error below 11 m within 200 meters [72]. Fermilab’ s ICARUS neutrino detector deployed three laser trackers for real-time reference point monitoring, ensuring errors could be corrected during hoisting [73]. DESY conducted magnet unit transportation deformation tests for PETRA IV to guarantee system stability [74]. HEPS employs vibrating wire technology to verify pre-alignment accuracy of magnet units [75]. As shown in [FIGURE:12], both HALF and HEPS use 3D trilateration network adjustment methods and Four-Laser Tracker Multilateration Measurement Systems (FLTMMS) for magnet unit pre-alignment. FLTMMS measurement performance is closely related to system layout, with ongoing research on four-laser tracker configurations. Simulation and experimental studies show the optimal station layout is a right-angled regular triangular pyramid structure, achieving point precision better than 10 m [76,77]. Additionally, FLTMMS performance is closely related to common point layout [78]. HALF optimizes common point deployment based on spatial uniformity and analyzes the influence of distance and angle on measurement performance [16,79]. To reduce dependence on common point layout, research is also exploring multilateral system configurations without orientation points [80].

Future FLTMMS research will focus on environmental factors affecting measurement precision, including temperature fluctuations, vibrations, and air turbulence. Real-time environmental monitoring using temperature sensors combined with error compensation models can dynamically correct measurement data, while vibration isolation bases and optimized measurement environments can effectively suppress external interference, improving overall system stability and reliability.

3.3 On-Site Installation and Smoothing Technology

To ensure stable accelerator operation, the core objective of alignment work is to guarantee equipment installation meets beam reference orbit physics design requirements. As shown in [FIGURE:13], overall accelerator performance heavily depends on relative alignment accuracy among components. Magnet misalignment can cause beam degradation and even prevent normal operation [26]. In recent years, research on "relative accuracy indicators" and "orbit smoothing" has gradually become a central focus in international particle accelerator alignment technology development.

Internationally, extensive research has been conducted on controlling orbit smoothness. SLAC employed Principal Component Analysis (PCA) combined with smoothing for 3D orbit data fitting, achieving locally continuous and globally robust smoothing [81]. DESY introduced cubic spline functions and objective function optimization in HERA alignment procedures to generate smooth curves and correct storage ring circumference [82]. To address more complex structures and higher smoothness requirements, researchers have gradually introduced mathematical interpolation and signal processing methods. IHEP uses Aspline functions to smooth mutual position errors at component joints, ensuring continuous derivatives and minimum curvature at all points [83]. The Pohang Accelerator Laboratory introduced z-transform low-pass filters for PLS error analysis to remove systematic errors. Case studies from 1995-1997 using low-pass filtering for smoothing analysis showed that increasing the cutoff frequency to 6 MHz placed quadrupole magnets within 0.3 mm of the smooth curve under 2σ conditions, maintaining relative position errors within 0.15 mm tolerance [84]. CERN early adopted the "carpenter' s plane method" in LEP, using sliding window local polynomial fitting with iterative outlier removal to develop PLANE smoothing software [85,86]. LHC installation and two long shutdowns (LS1, LS2) employed piecewise fitting under least squares principles combined with magnet tilt monitoring to identify settlement areas [87-89]. While these geometric smoothing methods offer strong mathematical stability, careful selection of sliding window size, step length, and polynomial order within windows is required. With deeper understanding of accelerator structures and physics, SPring-8 evaluated magnet error mode effects on closed orbit distortion using eigenvalue methods to optimize precise magnet alignment. KEK' s PANDA network adjustment software calculates network averages followed by Fourier fitting, ensuring curve periodicity while considering the number of correction magnets when selecting smoothing reference curves [90].

Domestically, Yu Chenghao proposed a best-fit smoothing method based on design geometric information for efficient automatic alignment [25,91]. Liu Zhonghe introduced a moving least squares smoothing strategy avoiding piecewise fitting and iterative processes [92]. The National Synchrotron Radiation Laboratory at the University of Science and Technology of China borrowed from PLANE software concepts to propose a "bulldozer-style" smoothing method: performing polynomial fitting within each window (8-9 magnets) and using smoothed regions to guide unsmoothed sections, gradually advancing [93]. Subsequently, they proposed a robust smoothing strategy based on Parzen window functions, validated with physics calculations showing significant reduction in β-function oscillations and improved beam stability [19]. HEPS introduced a "deviation smoothing method" abstracting magnets as inlet/outlet two-point systems, comparing deviations with adjacent devices and setting thresholds for iterative adjustment to achieve simple and efficient smoothing control. Different smoothing algorithms must be selected based on accelerator structure and on-site installation conditions, but the core objective remains: maximizing the number of magnets to be adjusted while meeting physics alignment requirements to enhance engineering efficiency.

As relative alignment precision requirements for accelerators and colliders continue increasing, smoothing has evolved from one-dimensional geometric empirical processing to comprehensive automated smoothing incorporating multi-dimensional modeling, error decoupling, and integrated beam performance feedback. In summary, the ultimate purpose of smoothing remains precise magnet unit alignment while meeting beam performance indicators. When developing smoothing strategies, on-site measurement conditions and operational requirements should be considered to ensure implementation feasibility.

3.4 Deformation Monitoring Technology Progress

Deformation monitoring technology plays a crucial role in particle accelerator alignment, particularly during long-term operation where equipment deformation and displacement can directly affect beam quality. The core task is real-time monitoring of deformation across accelerator equipment, especially displacement or deformation of critical components such as magnets, RF cavities, and bases. With advances in high-precision sensors and measurement instruments, deformation monitoring has evolved from traditional single-point offline monitoring to comprehensive online monitoring based on multi-sensor fusion, including distributed fiber optic sensing, 3D point cloud technology, and laser interferometry. In recent years, distributed fiber optic sensing technology has been gradually applied due to its long-distance capability, high sensitivity, and real-time monitoring. By deploying fiber optic sensors on accelerator equipment, minute deformations during operation can be monitored in real-time to ensure optimal equipment condition. Beyond fiber optic sensing, 3D point cloud technology also plays an important role by capturing high-precision 3D data of equipment surfaces through laser scanning or stereo vision, enabling precise deformation measurement and visualization. This technology significantly enhances deformation monitoring intuitiveness and data accuracy, enabling more refined and reliable deformation assessment. As technology advances, alignment reference network technology based on miniaturized sensors [94-96] has emerged, integrating data from multiple sensors to provide more accurate and efficient measurement results. Furthermore, digital twin technology [97] enhances deformation monitoring system intelligence by comparing real-time monitoring data with virtual models, enabling not only deformation prediction and early warning but also providing engineers with precise adjustment recommendations to effectively improve equipment operational stability and safety.

4. Challenges and Future Directions

Particle accelerator alignment technology has achieved significant progress over the years, but with continuous technological advancement and expanding accelerator scales, numerous challenges remain. Future alignment technology research and applications will face higher demands, requiring breakthroughs in current limitations and solutions to a series of technical problems [98-103]. [FIGURE:15] illustrates the main current challenges and future development directions.

4.1 Multi-Physics Coupled Measurement Technology

In large particle accelerators, coupling effects between different physical fields create complex influences on precise component positioning. For example, temperature changes can cause thermal expansion, while earthquakes or vibrations may induce minute displacements. These factors collectively cause component deformation, affecting beam quality and overall accelerator stability. Therefore, accurately modeling and compensating for coupling effects between different physical fields has become a critical challenge. Future development of more precise coupling effect compensation methods based on multi-physics simulation and real-time monitoring technology will be key to improving accelerator stability and precision.

4.2 High-Precision In-Situ Particle Accelerator Component Monitoring Technology

Long-term accelerator stability is a prerequisite for reliable experimental data. During long-term operation, components may experience minute displacement, deformation, or wear that can affect beam quality and accelerator performance. Traditional monitoring technologies often focus on single-point or short-term measurements, while modern accelerator operation demands far exceed traditional capabilities. Therefore, achieving high-precision, long-term stable monitoring systems—particularly real-time tracking of equipment deformation and temperature variations—will be an important future research direction. Novel technologies such as distributed fiber optic sensing and quantum sensing are expected to play significant roles in this field, and when combined with big data analytics and artificial intelligence, can enable comprehensive monitoring and intelligent prediction of accelerator facilities.

4.3 Artificial Intelligence Empowerment and Automated Alignment Technology

With rapid development in big data, artificial intelligence, and machine learning, intelligent and automated technologies provide new solutions for particle accelerator alignment. In the future, automated equipment will increasingly participate in accelerator installation, commissioning, and maintenance, achieving real-time precise adjustments through efficient robotic control and sensor data acquisition. Simultaneously, AI can optimize error correction during alignment through real-time data analysis and processing, providing intelligent prediction and fault diagnosis functions. Deep integration of intelligence and automation can not only improve alignment precision and efficiency but also significantly reduce human operation risks and costs. As accelerator component sizes increase and installation spaces become more complex, precise positioning and installation become increasingly difficult. Future combination of high-precision positioning technology with computer simulation will enable precise control and optimization of accelerator component positions. Through virtual simulation and augmented reality technology, designers and engineers can simulate accelerator installation processes in virtual environments, predicting potential issues and optimizing solutions in advance. This technology can improve design and construction precision while reducing repeated adjustments in physical testing and enhancing overall installation efficiency.

4.4 Alignment Process Uncertainty Expression and Standardization Technology

As particle accelerator design and manufacturing requirements become more complex, future alignment technology development will increasingly rely on integration and standardization. Through unified interface standards, integrated measurement systems, and intelligent data transmission and processing platforms, future particle accelerators will achieve more efficient and precise alignment and commissioning. Cross-disciplinary technical cooperation and the establishment of relevant standards and specifications can further enhance the reliability and global applicability of accelerator alignment technology.

Particle accelerator alignment technology, as a core technology ensuring system stability and beam quality, has achieved remarkable progress in recent years. Alignment plays an indispensable role throughout accelerator design, construction, and maintenance. From traditional geometric measurement methods to modern technologies integrating laser measurement, quantum sensing, and digital twins, alignment precision has gradually advanced from sub-millimeter to sub-micrometer and even nanometer scales. This progress has driven technological advancement in high-energy physics, synchrotron radiation light sources, free-electron lasers, and other fields, providing strong technical support for constructing higher-precision, larger-scale accelerators.

During the 12th to 14th Five-Year Plan periods, China has developed an independent intellectual property rights accelerator alignment technology system through major engineering projects including the Shanghai Light Source, Spallation Neutron Source, High Energy Photon Source, and Hefei Advanced Light Source. Breakthrough achievements such as four-laser pre-alignment technology, control network design and optimization technology, and superconducting cavity cryogenic alignment technology have been successfully applied in multiple projects, significantly improving installation precision and operational stability, and providing important practical experience and technical accumulation for China’ s accelerator development.

However, as accelerator scales expand and precision requirements increase, traditional measurement methods and technologies face unprecedented challenges. Particularly for future ultra-high-energy accelerator projects, alignment technology will encounter even more complex technical problems. Challenges including multi-physics coupling, uncertainty expression in alignment processes, and localization of ultra-precision instruments require continuous innovation in interdisciplinary integration, system optimization, and precision control. With continuous breakthroughs in new technologies and deep integration of multidisciplinary approaches, alignment precision will continue to improve, supporting the construction and application of more efficient and stable accelerator systems. Through sustained technological innovation and practical application of particle accelerator alignment technology, we will contribute “Chinese solutions” with high precision and reliability to global high-energy physics research, facilitating future construction and application of higher-precision, larger-scale particle accelerators.

Author Contributions

He Xiaoye: Drafted the introduction, challenges and future directions, and conclusion sections; conducted critical review of intellectual content; revised the final version. Wu Enchen: Drafted the introduction to particle accelerator alignment technology, alignment instrument progress, and control network design and measurement technology sections; integrated and revised the full manuscript. Ding Ting: Drafted the accelerator component calibration and pre-alignment technology progress section and revised the full manuscript. Zhang Qiuyu: Drafted the on-site installation and smoothing technology progress section and revised the full manuscript. Wang Xiaolong: Drafted the deformation monitoring technology progress section and revised the full manuscript. Lin Yiliang: Organized references and revised the full manuscript.

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