ALIGNMENT STRATEGY FOR HALF AND SOME RESEARCH PROCESS ON ALIGNMENT TECHNOLOGIES AT NSRL

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Abstract

Hefei Advanced Light Facility (HALF), a key mega-science facility, commenced civil construction in June 2023 in Hefei, China. The National Synchrotron Radiation Laboratory (NSRL) is leading this project. HALF is a 4th generation diffraction-limited synchrotron radiation light source, including a 192 m injector, a 138.4 m transport line, and a storage ring with a circumference of 480 m. Compared to the 3rd and earlier generation light source, it requires more stringent alignment accuracy. This paper outlines the alignment strategy developed for HALF, detailing the accuracy requirements for different components and the alignment procedures and techniques used at various stages of the project. These stages span from civil engineering and the installation of machine components to the implementation of deformation monitoring systems. Additionally, the paper discusses research efforts to enhance accuracy and efficiency during key phases, including the establishment of the control network, pre-alignment, installation and smoothing. Key innovations in these processes include automated simulation and measurement methods based on a measurement plan, the development of a pre-alignment system using four laser trackers, and algorithms designed to improve alignment accuracy. The above scientific research will be further deepened in the future to further assist in the alignment work of HALF and other large scientific devices.

INTRODUCTION

Hefei Advanced Light Facility (HALF) is a fourth-generation, diffraction-limited synchrotron radiation light source, which uses a full-energy linear accelerator as its injector. The facility comprises an injector approximately 192 meters in length, a transport line about 140 meters long, and a storage ring with a circumference of around 480 meters. In the first phase, 10 experimental beamlines and stations will be constructed. These stations will be positioned around the storage ring, extending along the beam's tangential direction.

The alignment task involves positioning and installing all equipment along the accelerator according to the particle accelerator's physical design specifications. This ensures the particles follow a smooth trajectory in spatial relation to the accelerator components. During the operational phase of the accelerator, continuous deformation monitoring is necessary to assess the impact of any geometric deformations on the accelerator's operating parameters. The most stringent alignment requirement applies to the installation of components within the storage ring. The technical requirements for the physical alignment accuracy of the accelerator are as Table 1:

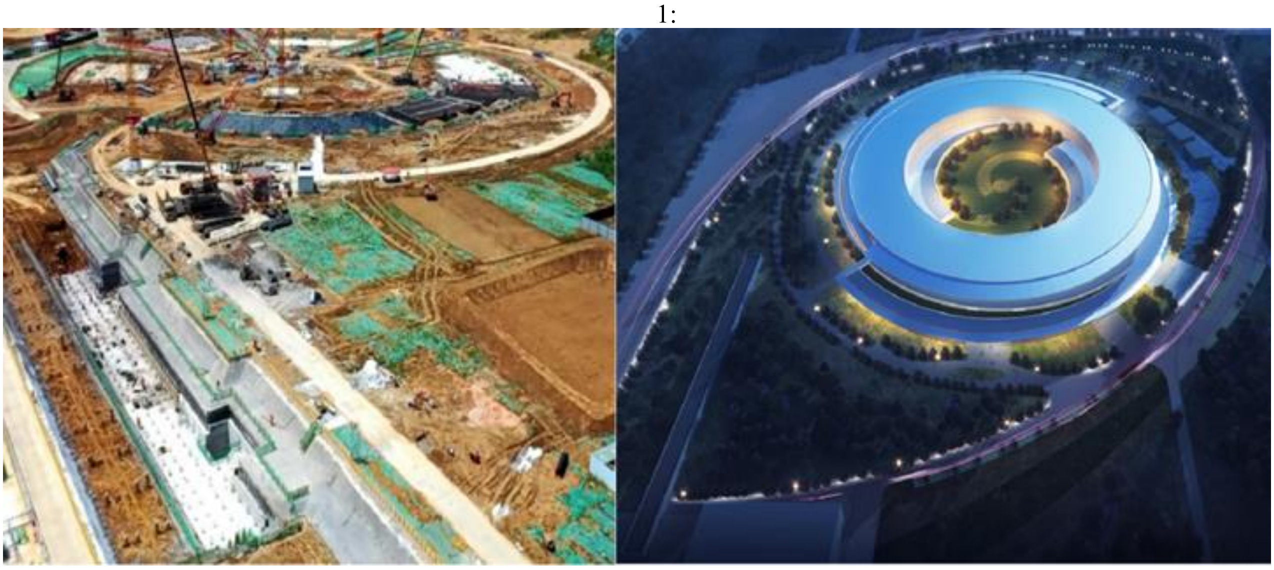

Figure 1: HALF civil engineering progress and conceptual layout

Table 1 Requirements of accelerator physical design for storage ring alignment

	Machine	Position accuracy (mm)			Attitude accuracy (mrad)		
		ΔX	ΔY	ΔZ	Δθx	Δθy	Δθz
Inside the girder	Quadrupole Sextupole Octupole	±0.03	±0.03	±0.15	±0.10	±0.10	±0.10
	Corrector dipole	±0.30	±0.30	±0.20	±0.20	±0.20	±0.20
	Bending dipole	±0.20	±0.20	±0.15	±0.10	±0.20	±0.20
Between adjacent girders	Magnet alignment girder	±0.05	±0.05	±0.20	±0.10	±0.10	±0.10
	Other machine	±0.20	±0.20	±0.30	±0.20	±0.20	±0.20

GENERAL STEPS OF ALIGNMENT

The alignment process for the HALF spans the entire construction of the light source. In the planning phase, it is crucial to determine the geographical location of the machine and establish a first-class control network. This network defines the overall coordinate system and ensures the spatial relationship among all parts of the accelerator. During civil construction, continuous monitoring of the first-class control network is required to maintain the accuracy of the relative positions within the network. Once civil construction is complete, a second-class control network is established around the tunnel where the equipment will be installed. The coordinates of the second-class control network are derived from the first-class network. Through the 2nd class control network, the local spatial coordinates can be restored in the overall coordinate system, and the installation of each accelerator installation unit based on the global coordinate system and the later deformation monitoring can be realized. To eliminate the rapid deformation of newly built buildings, it takes a certain time to stabilize the 2nd class control network after its construction, usually 3-6 months. During this period, it is necessary to continuously measure the 2nd class control network to ensure that all 2nd class outlets reach a stable state before the equipment installation starts.

To ensure a smooth trajectory for particle movement, a geometric smoothing process is applied to all installation units after the equipment is in place and before the machine is operational. This process eliminates abrupt changes in the geometric paths between adjacent components.

Additionally, to support the long-term stable operation of the machine and mitigate the effects of foundation settlement, equipment stress, and deformation on the geometric center of the particle beam, a deformation monitoring system is established. This system includes the Hydrostatic Leveling System (HLS) to monitor vertical foundation and support deformations, the Wire Positioning System (WPS) to detect lateral shifts in the equipment's geometric center, and the NIVEL tilt monitoring system to track the alignment of individual units. During scheduled maintenance shutdowns, large-scale deformation monitoring is conducted using laser trackers, photogrammetry systems, and other methods.

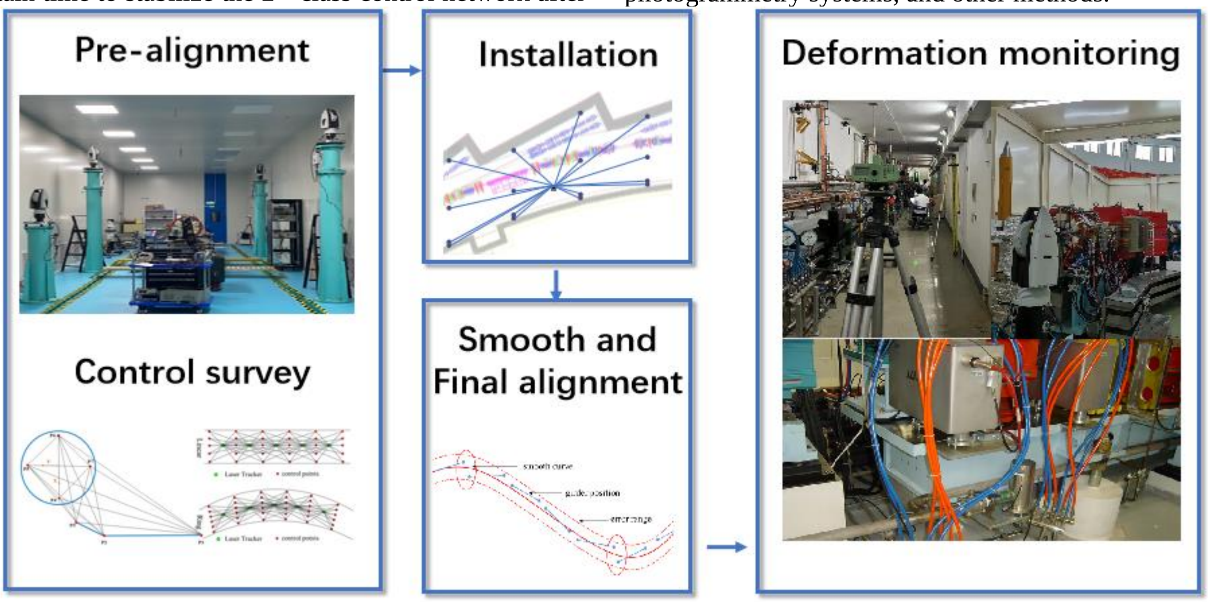

Figure 2 : General steps of alignment

DESIGN AND RESEARCH PROCESSING OF THE CONTROL NETWORKS

Design and research processing of the 1st class control network establishment

According to the overall layout of HALF, the 1st class control network needs to be able to control the relative relationship among the injector, the transport line, and the storage ring, considering the robustness and reliability of the network type and the simplicity of measurement. The overall layout is as follows.

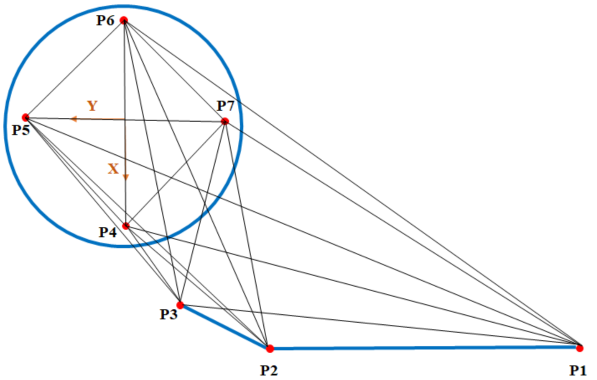

Figure 3: The control points of the 1st class control network

P1, P2, and P3 are in the tunnel of the straight line and the transport line. P1 is located 1 meter ahead of the electron gun.P2 is located at the end of the linear accelerator, and can ensure the visibility conditions between P1-P2 and P2-P3 as far as possible. P3 is located at the end of the transport line. P4, P5, P6 and P7 are arranged in the storage ring tunnel, in which the connecting line of P5 and P7 is parallel to the beam center line of the linac, and the connecting line of P4 and P6 is perpendicular to the connecting line of P5 and P7. The intersection of the lines P4-P6 and P5-P7 serves as the origin of coordinates, with the P5-P7 line representing the X-axis and the vertical direction as the Z-axis, forming the three-dimensional coordinate system based on the right-hand rule, which will be the total coordinate system of the whole accelerator. Above the points, intervisibility holes through the tunnel ceil are built to carry out GNSS measurement outdoors and the positions of GNSS on the roof-top are determined by laser plummet aimed at the points in the runnel.

The 1st class control point determines the coordinate system of the whole machine, which requires long-term stability. The 1st class control point mark is composed of two parts: the bedrock pile which is located on the bedrock and the base seat which is installed on the bedrock pile. The bedrock pile is made of reinforced concrete and falls into the breezy bedrock pit. The pile is separated from the building foundation and soil layer by the protective well, forming an isolated permanent mark that is only located on the bedrock and not disturbed by the ground building and soil layer. After a three-month stabilization period, horizontal and vertical deformation must be less than 20 microns per year. Considering the monitoring of foundation settlement in the tunnel and storage ring hall, the hydrostatic levelling system (HLS) should be installed on the upper end of the foundation pile, whose structure includes the forced alignment structure, the screw hole for installing the HLS sensor, etc. Fig 4(b) shows the structure of the upper-end face. The relationship between the construction of the 1st class control point, taking into account the HLS system, and the ground of the tunnel is shown in Fig 4(c) :

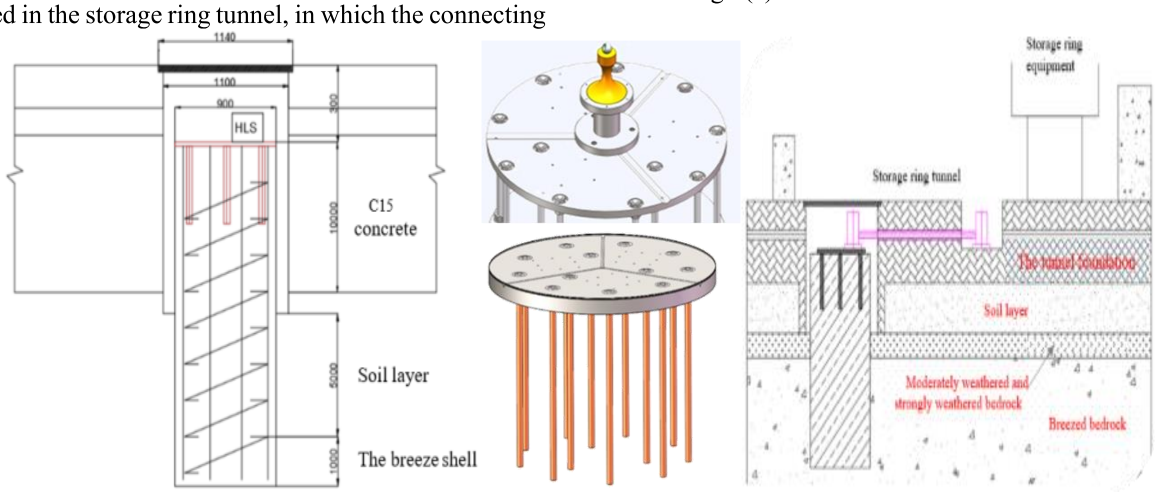

Figure 4: Structure design of 1st class control point (a: Structure diagram of foundation pile of 1st class control point; b: Schematic diagram of the upper-end face of the 1st class control point; c: Relationship between 1st class control point and the ground construction)

The 1st class control points will be constructed before any other main civil buildings and just after completion theodolite, total station, and level can be used to measure the 1st class control network to take advantage of the good intervisibility then. After other buildings start construction the intervisibility is broken, and then GNSS will be mainly used for the measurement of the 1st class control network. To make the data from different measurement methods consistent, GNSS measurement should be carried out in the early stage of civil construction, and the comparison of measurement accuracies should be carried out. According to the layout of the above control network, before the construction of civil buildings and the early stage of building construction, the conventional network measurement method based on the theodolite, level, total station, and other optical (photoelectric) instruments is adopted, and relevant processing software for adjustment calculation is used. At this time, the horizontal direction and elevation direction can be measured and calculated separately.

According to the research results of the HALF pre-research project, the precision of the simulated measurement and adjustment process of the 1st class control network has been analyzed. The instruments used include: LeicaTDA5005 total station: Angle measurement accuracy: 0.5", distance measurement accuracy: 0.6mm+1ppm; Leica DNA03 electronic level measuring system: accuracy ±0.03mm/km of round trip; Wild N3 optical level: accuracy ±0.02mm/km of round trip. The total station simulation calculation conclusion is as Table 2.

The biggest point error is ±0.05 mm, much better than the positional accuracy requirements in 1st class control network. This is ideally simulated measurement and calculation. In real-world conditions, measurement errors and environmental factors may increase this value, but it will remain within the acceptable threshold of ±3 mm for positional accuracy, which is the minimum requirement for positional accuracy.

As to GNSS measurement, the GNSS receiver is Leica GS16 which can receive satellite signals of GPS, GLONASS, Galileo, Compass, Beidou, and other systems. The nominal point measurement accuracy is 3 mm+0. 3ppm.The antenna phase center accuracy is required to be less than 1mm, and the repeatability of the antenna phase center is less than 1mm. The requirements for observation conditions are that GPS observation is little affected by weather and suitable for all-weather observation, except during thunderstorms. Observation parameters and requirements are set as satellite cutoff height Angle ⩾15°, the number of simultaneous observation satellites is 4, total number of effective observation satellites not less than 9, effective observation time of any satellite in each period ⩾ 15min, observation duration is 8 hours, and data sampling interval is 30 seconds.

Based on GNSS measurement data processing, LEICA's commercial software LGO is used for baseline calculation and 3D adjustment. After the baseline calculation is completed, check the baseline quality in time, which includes checking the repeatability of the baseline component and side length, the baseline calibration of each period, the disclosure of the independent ring, and the disclosure of the full length of the ring line. In the elevation direction, loop and cross round-trip closed measurements are made using 1 1-second self-leveling level with an accuracy of 1mm. The GPS 3D unconstrained adjustment is performed by taking the positioning result of a single point measured for 30 minutes or a known control point as initial data. Combining the unconstrained adjustment results and the leveling results, the data processing method of fitting leveling is adopted. The initial survey results of the 1st control network are formed based on the coordinates which are established by taking the leveling coordinates of GPS in the horizontal plane and the leveling adjustment elevation in the vertical direction and meanwhile, the correction of the horizontal plane around the ring center is taken. The data processing of simulated GNSS measurement in the HALF pre-research stage is as Table 3.

The above analysis shows that the two sets of measurement methods can meet the requirements of the precision of the 1st class control network.

Table 2 Coordinate adjustment and accuracy with total station

Name	X(m)	Y(m)	MX(cm)	MY(cm)	MP(cm)	E(cm)	F(cm)	T(dms)
P1	156.0140	-168.7200						
P2	156.0140	-44.9760						
P3	54.0189	57.0188	0.03	0.02	0.04	0.03	0.02	21.0931
P4	-0.0001	79.3937	0.03	0.03	0.04	0.04	0.02	34.5557
P5	-79.3937	-0.0002	0.03	0.04	0.05	0.04	0.02	67.3146
P6	0.0000	-79.3941	0.02	0.03	0.03	0.03	0.02	90.3037
P7	79.3941	-0.0001	0.02	0.02	0.03	0.02	0.02	4.4550
MX mean：0.03 MY mean:0.03 MP mean:0.04								

Table 3 Coordinate adjustment and accuracy with GNSS

Name	X(m)	Y(m)	MX(cm)	MY(cm)	MP(cm)	E(cm)	F(cm)	T(dms)
P1	156.0140	-168.7200						
P2	156.0140	-44.9760						
P3	54.019	57.0185	0.04	0.03	0.06	0.05	0.03	151.5032
P4	0.0001	79.3934	0.05	0.04	0.07	0.06	0.04	159.3943
P5	-79.3932	-0.0002	0.06	0.04	0.07	0.06	0.04	6.0016
P6	0.0002	-79.3940	0.04	0.03	0.05	0.04	0.03	17.4803

P7	79.3941	-0.0002	0.03	0.02	0.04	0.04	0.02	155.0030
		MX mean： 0.05		MY mean:0.04	MP mean:0.06			

Design and research processing of the 2nd class control network establishment

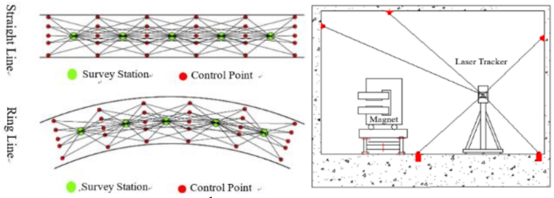

Figure 5: The 2nd class control network of HALF

The control points’ coordinates of the 2nd class control network, through which the recovery of local spatial coordinates in the general coordinate system can be realized, are obtained through the transmission of the 1st class control network. The process of installing units on-site and monitoring the deformation of the accelerator can all be based on the general coordinate.

The 2nd class control network is distributed around the accelerator machine, which serves as the basis for restoring the general coordinate system during the installation and is also the coordinate reference point for the position deformation monitoring during the operation of the machine. Considering the characteristics of three-dimensional measurement, the layout of 2nd class control points should be a full-space three-dimensional layout.

The 2nd class control points include ground points, wall points and roof points. The ground points are permanently bonded to the tunnel ground with epoxy resin, and the wall points are permanently fixed to the wall with expansion bolts. The ground point needs to be buried below the ground, and the upper-end face should be kept at the same height as the ground to avoid any inconvenience in accessing.

The control network measurement adopts a large range of intensive measurement methods for each station, at which a laser tracker measures 6 sections before and after it, to ensure that there are enough overlapped common points between two adjacent stations. In this way, each station measures about 60 control points, the measurement range is about 60 meters, and there are about 50 common points between two adjacent stations. For the ring tunnel control network, the measurement is conducted through closed-loop measurement along the ring, and for the linear control network, the measurement is carried out round-trip from the beginning to the end.

Laser trackers should be stably supported between two sections. The electronic horizontal bubble is adjusted to horizontal, and a scale bar with a fixed length calibrated metrologically is measured to verify the measurement accuracy of the instrument before measuring the control points. At the end of the measurement, the nearest and farthest points on both sides of the laser tracker sides of the instrument are measured again and the data are compared with those obtained in the first measurement to check whether the instrument moves during measurement. This method of "inner and exterior coincidence" is adopted to ensure the reliability of the measurement data.

The measurement accuracy of the control network is required as the absolute plane point accuracy is ±0.8mm, the absolute elevation point accuracy is ±0.6mm, the accuracy of relative plane point position is ±0.033mm, and the accuracy of relative elevation point position is ±0.030mm.

We adopt the Monte Carlo method for optimizing the control network configuration of HALF from the perspectives of quality and efficiency. The 210-meter linear accelerator control network of HALF was selected as the design object in 2024. The linear accelerator tunnel control network of HALF is simulated in 1:1 as in Fig. 6, to conduct the research on the influencing factors of the particle accelerator tunnel control network configuration, and to obtain the general conclusions.

Looking at the above-influencing factors and summarizing the influence of the above-influencing factors on the precision and accuracy, the design of the measuring distance, the density of measuring stations and the number of top points are positively correlated with the precision and accuracy, in which the improvement of the measuring distance and the increase of the density of measuring stations are better in terms of the precision's improvement, better in terms of efficiency, and lower in terms of cost compared with the latter. The horizontal coordinates and vertical coordinates of the top points in the cross-section and the straightness of the stations have no obvious correlation with the precision and accuracy, which need to be simulated and analyzed in the actual project. Under the specific network configuration studied in this paper, the uncertainty of the control network points is 0.187 mm. The absolute precision of the points is 42.59 micrometers.

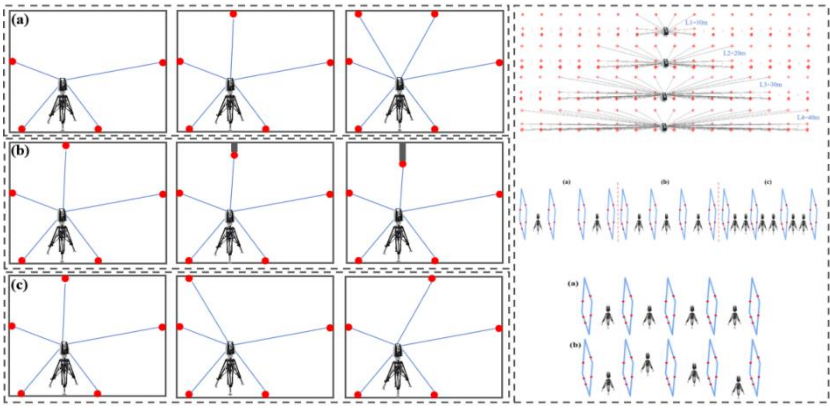

Figure 5 : The 2nd class control network of HALF

PRE-ALIGNMENT OF COMPONENTS

Pre-alignment of installation units based on four laser trackers

Fourth-generation diffraction-limited storage ring synchrotron light sources, such as HALF, require significantly higher installation accuracy, particularly in the horizontal direction for quadrupoles and sextupoles, compared to previous generations. In one installation unit, the lateral relative position accuracy of multipole magnets is better than 30 µm. Based on multi-station measurement with one laser tracker or single-station measurement with multiple trackers, the traditional side and angle adjustment methods can no longer meet the requirements of such high position accuracy. The primary source of measurement error in laser trackers is the angular measurement error, whereas the accuracy of tracker interferometric ranging (IFM) can reach 0.5 µm per meter. However, angular measurement errors are significantly higher; for instance, the AT901 tracker has a side length measurement error of 0.01 mm over 10 meters, but its angular measurement error can reach 0.075 mm, which is an order of magnitude higher than the side measurement error. To mitigate the larger angular measurement errors, a four-station laser tracker multilateration measurement system (FLTMMS) is used for joint measurements. This system establishes a spatial three-dimensional network for pre-alignment, significantly improving point measurement accuracy. This method is also called the laser tracker multilateration intersection method. The schematic diagram of the measuring system is shown in Fig 7 below:

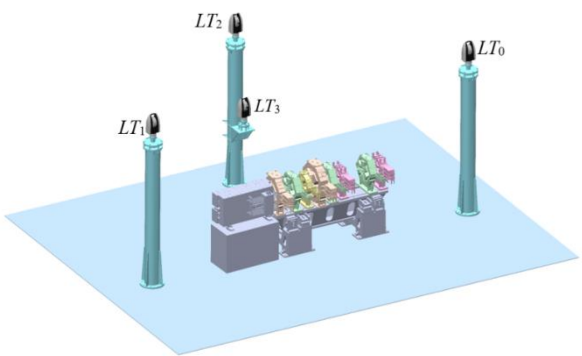

Figure 7: Schematic diagram of side length intersection of FLTMMS

In survey space the No. i（i =1、2、3…m） station S（Xi，Yi， Zi）measures the j (j =1, 2, 3...n) orientation points P (xj, yj, zj), the distance between them is dij, which is given by the formula as

$$d_{ij} = \sqrt{(X_i - x_j)^2 + (Y_i - y_j)^2 + (Z_i - z_j)^2} \tag{1}$$

The number of unknowns is 3 (m+n), and the number of equations that can be listed is m × n. The following conditions must be met to realize the point coordinate solution: mn⩾3(m+n), m and n are positive integers. For example, m is 4, n is at least 12. Therefore, the measured points must be more than 12 to obtain the solution of each point position including the coordinate values of the measuring station. The adjustment method is the rank-deficient free network adjustment of 3D trilaterational network. The 3D trilaterational network based on precision ranging values only has the length data but no position and azimuth information, so it has a rank deficiency.

$$A^T P A \delta X = A^T P l \tag{2}$$

In the above equation, A is a rank-deficient matrix, $N=A^TPA$ is a singular matrix, and the solution of the normal equation is not unique. To obtain a unique solution, additional constraints must be added.

$$G^T P_X \delta X = 0 \tag{3}$$

The additional constraint matrix G should satisfy

$$\begin{cases} rk(G^T) = rk(G^T P_X) = d \\ AG = 0 \\ G^T P_X G = I \end{cases} \tag{4}$$

Construct the objective function according to the principle of least squares:

$$\phi = V^T P V + 2K^T (G^T \delta X) \tag{5}$$

By solving the above function, the correction number of 3D coordinate parameters and their weight inverse matrix of measurement stations and orientation points can be obtained:

$$\begin{cases} \delta X = (N + P_X G G^T P_X)^{(-1)} A^T P l \\ Q_{\delta X} = (N + P_X G G^T P_X)^{-1} N (N + P_X G G^T P_X)^{-1} \end{cases} \tag{6}$$

Since the ranging error of IFM is ±0.5 µm/m, the weight can be assigned as

$$P_S = \left(\frac{1}{S}\right)^2 \tag{7}$$

Then the coordinate adjustment values of the laser tracker stations and the orientation points are

$$X = X_0 + \delta X \tag{8}$$

In the coordinate conversion and self-calibration processes of an FLTMMS, an unreasonable distribution of common points can lead to a loss of accuracy. A method for selecting common points based on uniformity used by the exclusive circles in the FLTMMS is therefore proposed. In this method, the coordinate transformation space is divided according to the uniformity in different directions. The feasibility of our method is compared and analyzed through coordinate conversion and self-calibration experiments. Simulations show that with the same number of common points, this method leads to higher accuracy in coordinate conversion and self-calibration. The proposed method compensates for the loss of accuracy due to aggregation of common points. Comparative analyses show a clear positive relationship between the accuracy improvement effect and the difference in uniformity. The distribution of common points will change the accuracy distribution of FLTMMS.

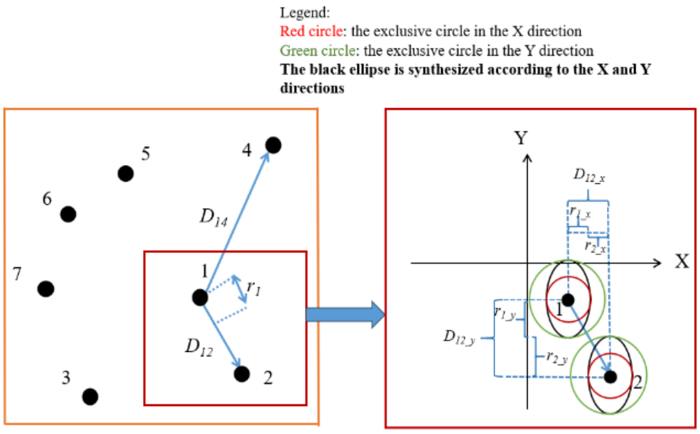

Figure 8: Diagram showing the exclusive circles

The spatial distribution of the four laser trackers will also affect the point accuracy of each measuring point. The Position Dilution of Precision (PDOP) is the error amplification factor, in other words namely, the ranging error of the laser tracker is multiplied by PDOP. Under the condition of a certain range the three-dimensional coordinate measurement accuracy of the space point varies with their different spatial positions. If the number of laser trackers is set as m, when $m \geq 4$, the line between each measuring station and the intersection point can be decomposed into m-2 tetrahedron. The attenuation factor of 3D position geometric accuracy is related to the volume V of these tetrahedrons.

$$PDOP \sim 1/V \tag{9}$$

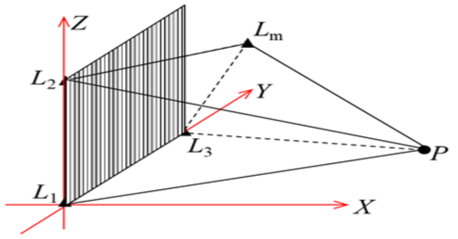

Figure 9: Correlation diagram of PDOP and volume V

With the increase of tetrahedron volume, the accuracy of the forward intersection measurement point will be improved. To improve the point position accuracy of rendezvous measurement by laser tracker, therefore, it is generally required that the PDOP value should be as small as possible, that is to say, the volume of the tetrahedron formed should be as large as possible.

Figure 10: FLTMMS layout diagram

It is evident from the PDOP calculation formula that simplifying the covariance matrix to a unit matrix can diminish the accuracy of the four-laser system parameters in the field of particle accelerator alignment measurements due to inaccurate random models. Extensive research has been conducted on this matter. Initially, we utilized fitting indicators for simulation experiments and demonstrated through comparison of fitting errors that the right-angled regular tetrahedron is the optimal configuration, achieving a transverse accuracy of 7.5μm for the magnetic unit, which satisfies the requirement of 10μm for the magnetic pre-alignment transverse accuracy. Focusing on the factors affecting the layout accuracy of the four-laser system, we conducted a thorough analysis of how angles and distances influence layout precision, discovering that angles can affect the distribution of accuracy and that distances in different directions exhibit varying sensitivity to precision, with the Y and Z axes (lateral) being the most sensitive. By integrating the precision requirements of HALF and the constraints of the on-site environment, appropriate layout strategies were proposed to provide effective guidance for the practical deployment of the four-laser system. However, the fitting error is not suitable for optimization as it slows down the process. Therefore, based on the uncertainties of the Four-Laser Tracker Measurement System (FLTMMS), we will propose environmental factor indicators and geometric layout indicators. The coupling of these two indicators will enhance the optimization speed.

The absolute ranging accuracy of the laser tracker can reach 0.5 μm /m, through simulation calculation, the spatial positioning accuracy of $0.01mm$ can be achieved by establishing a three-dimensional intersection side network. In the process of pre-alignment, the adjustment accuracies of the support mechanism and the locking mechanism should be considered. The adjustment accuracy of the support mechanism should be better than 0.006mm, and locking accuracy should be controlled less than 0.004mm. Based on the calibration accuracy of the magnetic center, the relative position accuracy of the magnetic center of each magnet obtained by pre-alignment is

$$\sqrt{0.01^2+0.006^2+0.01^2+0.005^2}=\pm 0.016mm \quad (10)$$

Thus, the accuracy of the magnetic center orientation position between adjacent magnets in the aligning unit can be obtained as $\pm 0.016\sqrt{2}=\pm 0.023mm$

Pre-alignment is done offline. After completing pre-alignment, the installation can be carried out through the process of lifting, transportation, lifting and positioning, during which causes deformation of the support system will affect the relative position between magnets. To meet the relative position accuracy of each magnet inside the installation unit which is better than ±0.030mm, it is necessary to ensure that the loss of accuracy caused in transportation is less than ±0.007mm, which will be tested through the actual operation process, and the method of lifting and transportation process will be continuously improved to meet these requirements.

During the pre-alignment process, the attitude angle of each magnet should be monitored in real-time by an electronic level, and the rolling angle and inclination angle should be less than ±0.1 mrad.

ON-SITE COMPONENTS INSTALLATION AND SMOOTHING

In the pre-alignment stage, in addition to determining the relative position relationship between each element inside the unit, the coordinate system of the unit and the coordinates of the alignment target points are also determined. At the same time, the attitude parameters of each magnet, as well as the inclination angle, rolling angle, and rotation angle are adjusted within the acceptable accuracy.

According to the theoretically designed position of the installation unit, generally, only the coordinate values of the center point (line) of each key element can be extracted on the drawing. Therefore, in pre-alignment, the coordinate values of center point (line) should be transferred to the outside aligning target seats in the component coordinate system according to the relative position relationship between the aligning target seats and the magnetic measurement results. At the same time, their relative positions are adjusted according to the designed theoretical values in the installation unit, and the overall alignment target seats of the installation unit are selected. When installing on-site, the alignment target coordinates are transferred to the global coordinate system, and making use of the lofting function of the laser tracker to accurately adjust them to the corresponding coordinates. Meanwhile, the attitude parameters of each component are monitored and adjusted to a reasonable precision range, and then the online installation of a unit installation is completed. An overview of component installation is shown below. Since there will be a severe deformation period just after the completion of the new building, the on-site installation should be carried out 6 months after the completion of the infrastructure. During this period, the alignment group will measure the 2nd class control network every half month to monitor its change speed and stability trend. The equipment can not be installed online until the deformation of the building and foundation is observed to be stable. It should be noted that the recovery accuracy of the global coordinate system of the 2nd class control network will greatly affect the installation and positioning accuracy of units. Therefore, it is necessary that the laser tracker near the installation position measures as many measurable points including control ones of 2nd control network and reference points on the devices as possible. Generally at a station the laser tracker has to measure 6 sections before and after it. In the process of component installation will involve the unification of the coordinate system, so the study of a high-accuracy datum transformation model is very necessary.

The coordinates corresponding to the global coordinate system $O-X'Y'Z'$ and the station coordinate system $O-XYZ$ are $[X'\,Y'\,Z']$ and $[X\,Y\,Z]$, and the principle is to unify the spatial three-dimensional coordinate values under different coordinate systems into the same coordinate system through the common point transfer. Where the scale transformation parameter is λ, which is usually taken as 1 in the same measurement system, the rotation matrix is R, the translation vector is $[Tx\,Ty\,Tz]^T$, and the corresponding mathematical model is constructed according to the above parameters as equation (11).

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \lambda R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} Tx \\ Ty \\ Tz \end{bmatrix} \quad (11)$$

There are many expression models for solving the rotation matrix in coordinate transformation, and the corresponding solution methods of different models are somewhat different. In the helmert model introduced here, the rotation matrix R is a function matrix of ω, φ and κ, where ω, φ and κ represent the rotation angles of the coordinate system to be transformed around its X-axis, Y-axis, and Z-axis, respectively. The specific functional relationship is as follows:

$$R(\omega,\varphi,\kappa)=\begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix}=R(\omega)\cdot R(\varphi)\cdot R(\kappa) \quad (12)$$

Expand the above formula to get the factors of the rotation matrix:

$$\begin{cases} a_1=\cos\varphi\cos\kappa \\ a_2=-\cos\varphi\sin\kappa \\ a_3=-\sin\varphi \\ b_1=\cos\omega\cos\kappa-\sin\omega\sin\varphi\cos\kappa \\ b_2=\cos\omega\cos\kappa+\sin\omega\sin\varphi\sin\kappa \\ b_3=-\sin\omega\cos\varphi \\ c_1=\sin\omega\sin\kappa+\cos\omega\sin\varphi\cos\kappa \\ c_2=\sin\omega\cos\kappa-\cos\omega\sin\varphi\sin\kappa \\ c_3=\cos\omega\cos\varphi \end{cases} \quad (13)$$

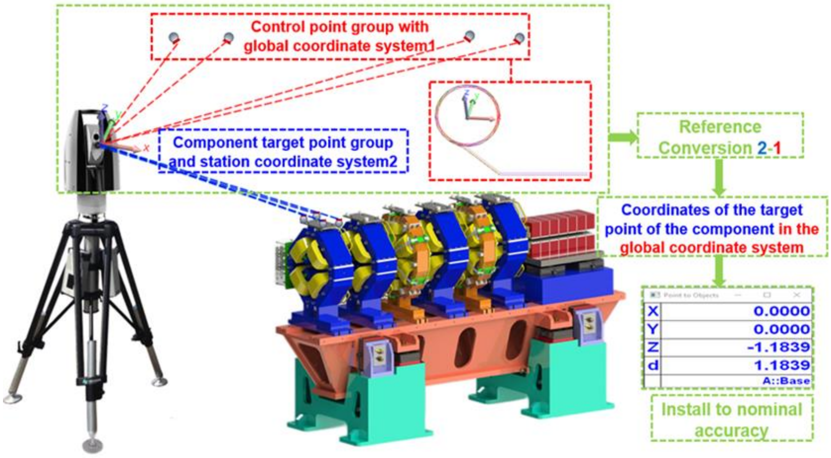

Figure 11: General overview of baseline transformation during installation

A laser tracker is used to set up a station near the unit to be installed and restore the coordinate system through the measurement of the control network. A unit is installed in the station and the upstream and downstream installation units are monitored. The point position measurement accuracy of the tracker in a single measuring station is ±0.03mm. Based on the positioning accuracy of the coordinate system of the mounting unit, the transverse position accuracy is focused on specially, and the support adjustment locking error is ±0.005mm, then the transverse installation accuracy is estimated as follows:

$$\sqrt{0.03^2+0.03^2+0.005^2}=\pm 0.043mm \quad (14)$$

This accuracy meets the requirement of ±0.05mm transverse position accuracy of adjacent units.

In the adjustment process of the installation unit, the above steps focus on the transverse position relationship, while the accuracy along the beam direction (longitudinal) is a second-class consideration. To meet the requirement that the longitudinal relative position accuracy is better than ±0.15mm, the longitudinal positioning accuracy must meet the following relationship:

$$\Delta s<\frac{\sqrt{0.15^2-0.05^2}}{2}=\pm 0.07mm \quad (15)$$

During the installation process, the electronic level must be used to monitor the attitude angle of each magnet on the installation unit in real time. Under the condition that the position accuracy meets the requirements, the attitude angle should be within the allowable error range, that is, the rolling angle (roll) and inclination angle (pitch) should be less than ±0.01mrad. The torsional pendulum angle (yaw) is determined by the relative position of adjacent transverse positions of adjacent units. That is, for installation units 1m apart, the relative torsional pendulum angle is:

$$\Delta yaw<\frac{0.05\times\sqrt{2}}{1}\approx\pm 0.07mrad \quad (16)$$

Absolute error characterizes the deviation between the particle accelerator components and the ideal position and is used to control the distortion of the overall shape of the particle accelerator. Relative error refers to the alignment deviation between adjacent components of the particle accelerator. The performance of the particle accelerator depends more on the relative position relationship between the magnets. Smoothing is a mature final alignment technology, which is used to further accurately align the relative position relationship between units after the common support installation, to eliminate the deviation jump between adjacent units. A robust smoothing analysis strategy aimed at reducing relative position errors is presented here to smooth the magnetic core orbit. First, we pre-process the original data based on gross error detection. Then, we do a smooth analysis of the data of the magnetic centers' orbit and iteration by using the curve fitting of the Parzen-window function. Finally, the physical accelerator calculation is utilized to terminate the iteration.

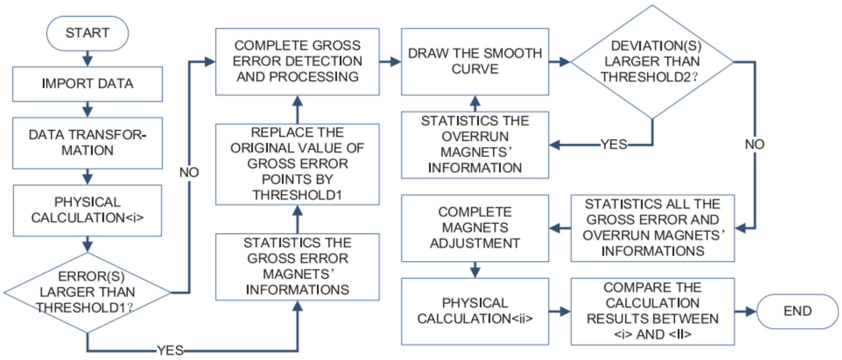

Figure 12: Flowchart of the proposed strategy

We chose the proposed strategy to smooth the orbit data in which we set the actual values of threshold1 and threshold2, as $3\delta_1$ and 0.1mm, respectively. Fig 13 shows the smoothing analysis results in the X and Y axes, respectively, which indicates that all the gross error points have already been detected and processed. Meanwhile, the overrun points are also adjusted, and the final fitted curve is under an envelope of actual positions with ± 0.1mm error. The results show that the actual center positions of the magnets have significantly improved.

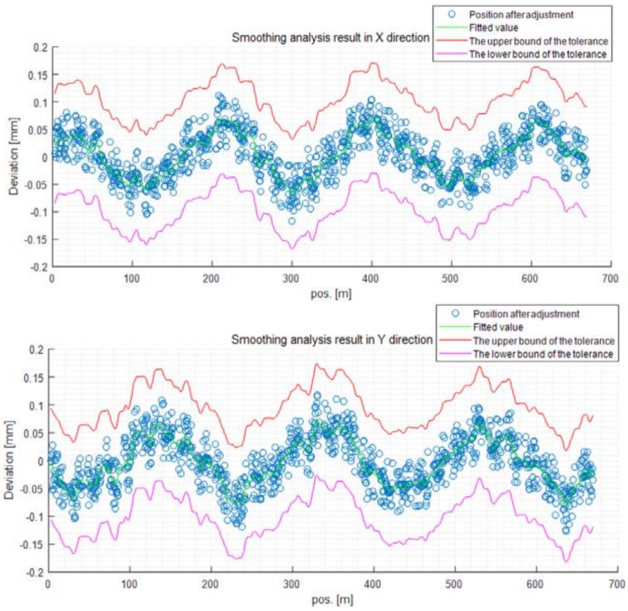

Figure 13: Results derived from the proposed strategy

ACCELERATOR DEFORMATION MONITORING

Monitoring of uneven settlement of foundation

The uneven settlement of the foundation is especially obvious in the new accelerator, so it is necessary to set up a monitoring system. A Hydrostatic Levelling System (HLS) is an effective tool for monitoring the uneven settlement of the foundation.

HLS can monitor the uneven settlement of the ground base in real time for a long time, and can automatically collect, transmit, and save data. Through the accumulation and analysis of long-term data, it can also judge the trend of foundation change and can be compared with machine operation data to find the relationship between foundation change and machine operation parameters.

The HLS layout will be linear along the linac and the transport line, with the 1st class control points P1, P2, and P3 as the stable reference points. In the storage ring part, HLS can be laid along the storage ring tunnel. The overall settlement monitoring can be realized through common point overlap, and the 1st class control points P4, P5, P6 and P7 in the storage ring are taken as the stable reference point.

In the injector tunnel or the storage ring tunnel, the HLS layout should not occupy the surface space, so it is necessary to design and construct water pipe grooves. Grooves with a depth of not less than 300mm and a width of not less than 300mm should be built near the supports inside the machine in the storage ring tunnel, and the distance between the outer edge of the grooves and the inside of the supporting foot of the machine should be 100mm. The grooves can be irregular circular layouts or curved layouts. The upper-end face of the steel plate or concrete prefabricated plate cover is flush with the ground. Layout of grooves used for HLS as Fig 15.

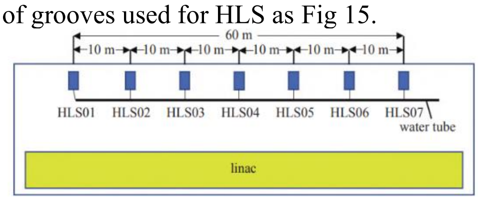

Figure 14: HLS layout of the injector tunnel

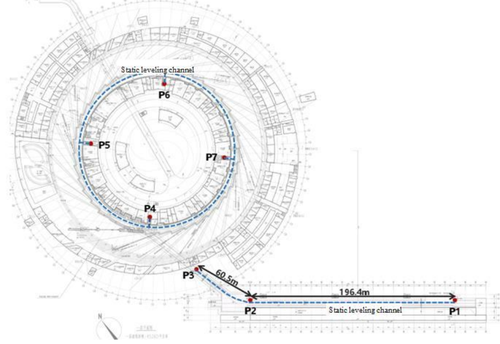

Figure 15: Civil trench diagram of HLS

The upper-end face of the 1st class control point is designed and installed with a stable stainless steel upper-end face, on which the central target point is reserved, the fixed slot (point) of the total station support is reserved, and screw holes for installing the HLS sensor are reserved. The upper end of the control point should be some distance below the ground surface. Enough space between the protection cover and the upper end of the point should be reserved to install the HLS sensor.

Component deformation monitoring

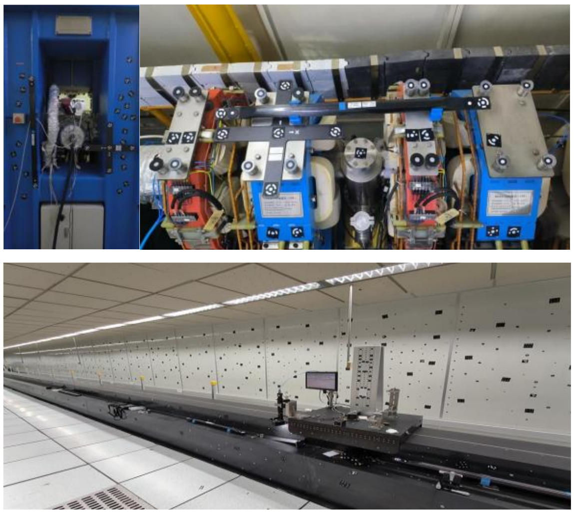

Figure 16: Close-range photogrammetry monitoring

After successful operation of an accelerator, it is essential to monitor the deformation of its components. Typically, laser trackers are used to monitor the deformation of components such as the Quadrupole, but their operation is somewhat cumbersome. Therefore, it is planned to use close-range photogrammetry to monitor the deformation of the accelerator components in the future, as shown in Figure 16. This method can complete the measurement task quickly and efficiently.

SUMMARY

HALF has broken ground in 2023, and the machine commissioning will be finished by the end of 2026 as planned. All design work will be carried out in an orderly manner, and the alignment work from scheme design, instrument purchase, and experimental platform construction to human resource preparation has been underway, which will ensure the progress and quality of the project.

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