The Primary Control network of HLSⅡ*

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Abstract

To make sure the high accuracy requirement of alignment and installation of HLSⅡ, the high accuracy control network is necessary. The primary control network provides high accuracy reference to local control network. After optimization design that using Monte-Carlo method, according to the structure characteristic of HLSⅡ, the primary control network is measured by several different instruments, such as: Laser tracker, Total station, plummet. The accuracy of actual primary control network meets the requirements of design project; it provides solid foundation for subsequent project.

Introduction

Hefei Light Source（HLS）was designed and constructed in the 1980s, formal opened to outside in 1992. From June of 2012, on the basis of the NSRL, HLS was having a major renovation, it is named Hefei light source-II(HLSII). The HLSII will be a new state-of-the-art, low-energy electron storage ring (800 MeV) designed to deliver world-leading intensity and brightness with a 40 nm-rad minimum horizontal emittance. The subject of the HLS-II includes a 73.435 meters linac accelerator and a 66.13 meters storage ring[1].

According to the requirement of accelerator physics, location accuracy of components are better than 0.2mm; even more some important equipments, transverse location accuracy are better than 0.08mm[2]. Achieving such a high accuracy at a large scale space, it is a huge challenge for geodesy group of HLSⅡ. Building a primary control network that high accuracy is first step and most important step that achieve the goal.

By observing and calculating the control points which distribute in the linac tunnel and synchrotron ring, the relationship of relative position is obtained. The primary control network has two important functions, first, making sure the relative relationship of linac and synchrotron ring; second, restraining the cumulative error of local control network.

Project design of the primary control network

Based on the structure characteristic of HLSⅡ, by consulting the design methods of other particle accelerators, triangulateration network is considered to be the most suitable option. By combined using several different instruments such as: Laser tracker, Total station, Level etc, the optimal coordinate values of control points of adjustment are obtained.

The primary control network design on the drawing

The datum points of initial building of Hefei light source are absolute reference all the time. It consists of seven metal pillars P01，P02，P03,P25，P26，P27，P28 that have forced centering devices and four datum points R01，R02，R03，R04 located on the synchrotron ring.

In the process of the upgrade, because of the influence that the obstruction and other reasons, some points can't be observed directly. By using the more advanced instruments and simplify the original primary control networks, the points that P01,P02,P03,P25，P26，P27，P28 are reserved, and a point is added at the middle of transport line. Then, according to the order, naming this points P1，P2，P3，P4，P5，P6，P7，P8. The line that connects P1 and P3 is X axis, P3 is positive direction. In the same way, the line that connects P2 and P4 is Y axis, P4 is positive direction. The point of interaction is original point, building a coordinate system. Plummet is used to project the points P5 and P6 that located in the transport line to synchrotron ring, naming them P5A and P6A. Taking no account of projection error, the coordinate value that P5, P6 and P5A, P6A are same. Laser tracker is used to repeat survey the P1-P4, and adjusting them to reach the error range, building coordinate system, the coordinate value of P5A and P6A are obtained. Then total station is used to survey the primary control network of linac and transport.

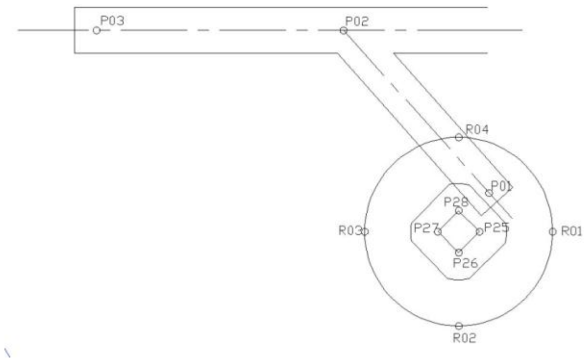

Fig.1：Layout of datum points of initial building

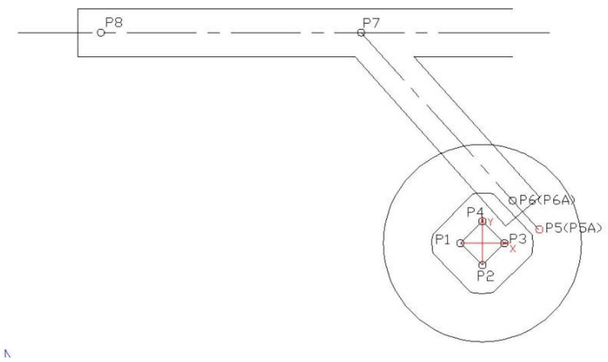

Fig.2：The layout of primary control network of HLS Ⅱ

Optimal design of primary control network

Through the drawing design, the shape of control network can be determined, and same time, implementer plan is also determined. According to the purpose and requirement of accuracy, several different plans are designed; by comparing these plans, the most suitable plan is determined as the final plan.

Optimal design of the primary control network can be expressed by formula:

$$\begin{aligned} &\min\left\{Z\left(x\right)\right\} \\ &g_i\left(x\right)\le 0 \ \text{i=1, 2, 3,}\cdots \qquad (1) \\ &h_i\left(x\right)=0 \ \text{j}=1,\ 2,\ 3,\cdots \end{aligned}$$

In formula， $Z\left(x\right)$ is objective function and $g_i\left(x\right)\le 0$ is inequality constrain，$h_i\left(x\right)=0$ is equality constrain， x is design variable. During the optimal design，design variable x， objective function $Z\left(x\right)$ and constrain $g_i\left(x\right)$， $h_i\left(x\right)$ are determined by goals of control network. The goals of the primary control network include：(1) Making sure the accuracy of control network；(2) Having more redundant observation for improving the result of adjustment; (3) Adding points and observing are necessary to meet the requirement of cost.

A is design matrix，weight matrix P is the inverse of weight matrix of observation vector coordinate factor matrix Q_x， so the coordinate factor matrix Q_x can be derived

$$\left(A^T PA\right)^{-}=Q_X \qquad (2)$$

Optimal design of control network is divided into four categories, the optimal design of the HLS Ⅱ primary control network is third category：improve design；Fixed parameter Q_x , A and P are undetermined by parameters. On the base of the primary control network, designing the new points，and adding new observed values to meet the requirement of Q_x [3].

The accuracy of control network is determined by the RMS of weakest ranging or the RMS of weakest point. According to the design experience of control network and the observation of drawing design, the distance of P7 and P8 is beyond 80m, and without other points between them, P8 is possibly the weakest point and the ranging of P7P8 is weakest ranging. The guess is confirmed by the computer simulation later.

Simulation method of Monte-Carlo is used to produce a set of pseudo-random numbers, simulating a set of observation data and making a series of simulation experiences, finally an optimal solution can be obtained. According to the fact of HLSⅡ, adding one or two points between the P7 and P8, calculating and obtaining three different results about P8(Table.1).

Table.1：The calculating results of three different design

Project design	The RMS of P8		
	$M_X\,(mm)$	$M_Y\,(mm)$	$M_P\,(mm)$
Without points	0.64	0.72	0.96
Adding one point P9	0.63	0.67	0.91
Adding two points P9，P10	0.62	0.63	0.88

According to the Table.1, by comparing the error of P8 of different design projects, the accuracy of P8 that adding two points P9 and P10 enhances 10% than without adding points. The third project is elected to be the final project.

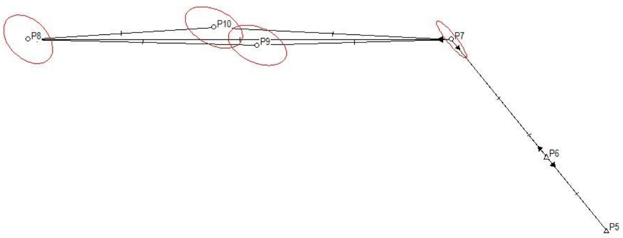

Fig.3：The primary control network of error ellipse

The actual measurement of the primary control network

According to the structure characteristic of HLS Ⅱ and the characteristic of different instruments, laser tracker, total station, plummet and level are used jointly. From the June of 2012, the primary network was measured.

The structure design and distribution of the primary control network points

Cone design is adopted to match the Ø 38.1 target bar, the bar diameter of different instruments are same, it benefits to exchange. Because of the error of machining, the actual touch is three points touch, and the positional repeatability is better than 0.01mm [4].

Fig.4：The target holder of the primary control network

Instruments and software

The model of laser tracker is Leica LTD840, the total station is TDA5005, and the plummet is NL. In order to ensure the precision of this instrument, they were calibrated before measuring. The ranging accuracy of laser tracker is better than 0.03mm, and angular accuracy is better than 0.2″[5]. The angular accuracy of total station is ±0.5″, the ranging accuracy is 0.5mm in the range of 200m. The plummet can offers a high-accuracy perpendicular, the accuracy of it is 1:200000[6].

The measurement software of laser tracker is Spatial Analyze, it is developed by NRK Company, and some instruments can work at the same time on it.

Fig.5：Instruments

Actual measuring

First, N3 level was used to measure the level of P1-P4, and adjusted them at the same level value. Second, laser tracker was used to measure the X, Y coordinate values of P1-P4. Third, the function of Best-fit was used to compare the measurement value with theory value, and adjust them. Repeating the second and third steps, the actual position of P1-P4 was similar to the theory. The line that connects P1 and P3 is X axis, P3 is positive direction. In the same way, the line that connects P2 and P4 is Y axis, P4 is positive direction. The point of interaction is original point, building a coordinate system. Because of the reason of actual naming, P5 was named TGA19. Plummet is used to project the points TGA19 and P6 that located in the transport line to synchrotron ring, naming them P5A and P6A. Taking no account of projection error, the coordinate value that TGA19, P6 and P5A, P6A are same. Then total station is positioned at the points TGA19, P6, P7, P8 to measure the ranging and angular. Because of the ranging of P7P8 beyond the 80m, in order to enhance the accuracy of network, adding two points between the P7P8, two points of local control networks named P9 and LWB21 were choose for saving costs. Four observation sets were measured by the total station [7].

Fig.6：Actual measurement of the primary control network

Adjustment and accuracy assessment

The measurement data is analyzed after actual measuring, then making an indirect adjustment and accuracy assessment.

Indirect adjustment

The primary control network is triangulateration network, including ranging measurements and angular measurements. The error functions of range observation:

$$\text{L+v=}S^0+\frac{\Delta X^0}{S^0}(\hat{x}_j-\hat{x}_i)+\frac{\Delta Y^0}{S^0}(\hat{y}_j-\hat{y}_i) \quad (3)$$

$$\hat{\text{L}}\text{=L+v=}\sqrt{(\hat{X}_j-\hat{X}_i)^2+(\hat{Y}_j-\hat{Y}_i)^2} \quad (4)$$

$$\Delta X^0=X_j^0-X_{\text{i,}}^0$$

$$\Delta Y^0=Y_j^0-Y_{\text{i}}^0$$

$$S^0=\sqrt{(\Delta X^0)^2+(\Delta Y^0)^2}$$

$$\text{v}_{\text{ij}}=-\frac{\Delta X^0}{S^0}\hat{x}_i-\frac{\Delta Y^0}{S^0}\hat{y}_i+\frac{\Delta X^0}{S^0}\hat{x}_j+\frac{\Delta Y^0}{S^0}\hat{y}_jS^0\text{-}l$$

$$l=L-S^0 \quad (5)$$

$\hat{X}_i$, $\hat{Y}_i$, $\hat{X}_j$, $\hat{Y}$ are the adjustment values of undermined points; $\hat{L}$ is the adjustment value of range distance and L is the measured value, v is the correct value; $X_i^0, \text{Y}_i^0, X_j^0, \text{Y}_j^0$ is the approximate coordinate value and S_0 is the approximate range;

The error functions of direction observation：

$$L+v=\hat{\alpha}_{ij}-\hat{\alpha}_{ik} \quad (6)$$

$$\overset{\wedge}{\alpha}=\alpha^0+\delta_\alpha \quad (7)$$

$$l=L_i-(\alpha_{ij}^0-\alpha_{ik}^0)=L_i-L_i^0 \quad (8)$$

Formula (7) and (8) into the formula (6)

$$v_i=\delta_{\alpha_{ij}}-\delta_{\alpha_{ik}}-l_i \quad (9)$$

And

$$\delta_{\alpha_{ij}}''=\frac{\rho''\Delta Y_{\text{ij}}^0}{(S_{ij}^0)^2}\hat{x}_i-\frac{\rho''\Delta X_{\text{ij}}^0}{(S_{ij}^0)^2}\overset{\wedge}{\text{y}}_i-\frac{\rho''\Delta Y_{\text{ij}}^0}{(S_{ij}^0)^2}\hat{x}_j-\frac{\rho''\Delta X_{\text{ij}}^0}{(S_{ij}^0)^2}\overset{\wedge}{\text{y}}_j \quad (10)$$

Formula (10) into the formula (9)

$$v=\rho''\left(\frac{\Delta Y_{ij}^0}{\left(S_{ij}^0\right)^2}-\frac{\Delta Y_{ik}^0}{\left(S_{ik}^0\right)^2}\right)\hat{x}_i-\rho''\left(\frac{\Delta X_{ij}^0}{\left(S_{ij}^0\right)^2}-\frac{\Delta X_{ik}^0}{\left(S_{ik}^0\right)^2}\right)\hat{y}_i$$
$$-\rho''\frac{\Delta Y_{ij}^0}{\left(S_{ij}^0\right)^2}\hat{x}_j+\rho''\frac{\Delta X_{ij}^0}{\left(S_{ij}^0\right)^2}\hat{y}_j \quad (11)$$
$$+\rho''\frac{\Delta Y_{ik}^0}{\left(S_{ik}^0\right)^2}\hat{x}_k-\rho''\frac{\Delta X_{ij}^0}{\left(S_{ik}^0\right)^2}\hat{y}_k-l$$

L is the angular observation and v is the correct value, i, j, k are undermined points; $\overset{\wedge}{\alpha}$ is the azimuth angle, α^0 is the approximate azimuth angle and is the correct value of azimuth angle.

The observation value of HLS Ⅱ has nine angular observations and eight range observations. Because of all the values of range observation are slant ranges, it is necessary to transform them to be the horizontal distances. 17 error functions were obtained, and necessary observations are $t = 2 \times 4 = 8$.The adjustment value of undermined points are the parameters:

$$\hat{X} = \left[\hat{X}_{P7}, \hat{Y}_{P7}, \hat{X}_{P8}, \hat{Y}_{P8}, \hat{X}_{P9}, \hat{Y}_{P9}, \hat{X}_{LWB21}, \hat{Y}_{LWB21} \right]^T$$

Calculating the approximate coordinate and azimuth accord to the incremental formula

Table.2：Approximate coordinate of undermined points

Points name	X(m)	Y(m)
P7	44.006	-21.098
P8	44.014	-101.072
P9	42.886	-57.729
LWB21	46.26	-65.966

Table.3：Azimuth of ranging

Direction	Azimuth ° ′ ″	Direction	Azimuth ° ′ ″
P6P5	140 55 20	P7LWB21	272 52 33
P6P7	321 0 22	P8P7	89 59 39
P7P9	140 58 25	P8P9	91 29 27
P7P5	268 14 55	P8LWB21	86 20 21
P7P8	269 59 39		

Weight of ranging and angular，the RMS of unit weight is $\sigma_0 = 0.5''$ and σ_β is the RMS of measuring angular, σ_{S_i} is the RMS of measuring range; so the angular weight is

$$P_{\beta_I} = \frac{\sigma_0^2}{\sigma_\beta^2} \qquad (12)$$

The ranging weight is

$$P_{S_I} = \frac{\sigma_0^2}{\sigma_{S_i}^2} \qquad (13)$$

Because of the accuracy index of TDA5005 is known，and according to the formula (12) and (13)， weight matrix P can be obtained

$$P = \mathrm{diag}\left(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1\right)$$

According to the formula (5) and (9), calculating B(unit： m) and l(unit： mm) of error function

$$B_{17\times8} = \begin{bmatrix} \text{-0.7772,0.6292,0,0,0,0,0,0} \\ \text{-0.7768,0.6296,0,0,0,0,0,0} \\ \text{0.305,0.999,0,0,-0.0305,-0.9999,0,0} \\ \vdots \\ \text{0,0,0,0,0.0638,-0.9979,-0.6385,0.9979} \\ \vdots \\ \text{0,0,-0.3743,5.8465,0,0,0.3742,-0.5464} \end{bmatrix}$$

$$l_{1\times17} = \left[-0.996315, -0.114728, -2.012124 \cdots -8.022675, -0.177201\right]^T$$

error function：

$$V = B\hat{x} - l \qquad (14)$$

B is the coefficient matrix of error functions. According to the least squares method, $\hat{x}$ is match to $V^{T}PV = \min$, transposition

$$B^{T}PV = 0 \qquad (15)$$

$$B^{T}PB\hat{x} - B^{T}Pl = 0 \qquad (16)$$

$$N_{BB} = B^{T}PB,\ W = B^{T}Pl$$

simplify(16)，obtaining the normal equation

$$N_{BB}\hat{x} - W = 0 \qquad (17)$$

$$\hat{x} = N_{BB}^{-1}W = (B^{T}PB)^{-1}B^{T}Pl \qquad (18)$$

The unknown number of the formula of（14）and（15）are 17 and 8，the number of the function are 25，unique solution. Canceling V ：

N_{BB} is non-singular matrix，and $R(N_{BB}) = 8$, $\hat{x}$ has unique solution[8]：

Put B, P, l into the (18) formula：

$$\hat{x} = [-0.342, 0.897, -1.091, 0.885, -0.307, -6.931, -0.936, 0.72]^{T}$$

Adding the $\hat{x}$ to the X^{0} , equal $\hat{X}$ (unit： m)

$$\hat{X} = [44.0056, -21.0971, 44.0129, -101.0711, 42.8857, -57.7359, 46.2591, -65.9653]^{T}$$

Accuracy assessment

The actual RMS of unit

$$\hat{\sigma}_{0} = \sqrt{\frac{V^{T}PV}{\mathrm{r}}} = 0.4498''$$

According to the inverse matrix of weight N_{BB}^{-1} ， the reciprocal of P can be obtained. Error of every undermine points：

$$\hat{\sigma}_{P7} = \hat{\sigma}_{0}\sqrt{Q_{X_{P7}} + Q_{Y_{P7}}} = 0.61$$

$$\hat{\sigma}_{P8} = \hat{\sigma}_{0}\sqrt{Q_{X_{P8}} + Q_{Y_{P8}}} = 0.87$$

$$\hat{\sigma}_{P9} = \hat{\sigma}_{0}\sqrt{Q_{X_{P9}} + Q_{Y_{P9}}} = 0.91$$

$$\hat{\sigma}_{LWB21} = \hat{\sigma}_{0}\sqrt{Q_{X_{LWB21}} + Q_{Y_{LWB21}}} = 0.91$$

Comparing with software

COSA is developed by Wuhang University, and it also is a commercial software . It is used to calculate the primary network and the result is compared with the result of hand computation.

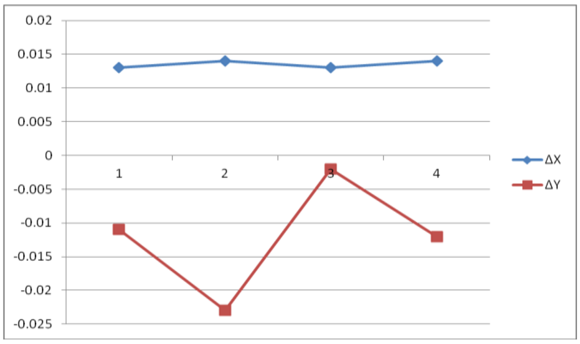

Fig.7 Comparing with COSA

The biggest error of the DIF is 0.023mm. The error is allowed.

Conclusion

After a thoughtful arrangement, the project of HLS Ⅱ is successful; Indirect adjustment is used to adjust the measuring data; the accuracy of the primary control network is meeting the requirement. The primary control network provides the global constraint for the project, and restraining the error accumulation of local control network, making sure the smoothing of the project.

February of 2014, the light was success to lead, and it also proves the success of the upgrade project.

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