
# The Primary Control network of HLS Ⅱ

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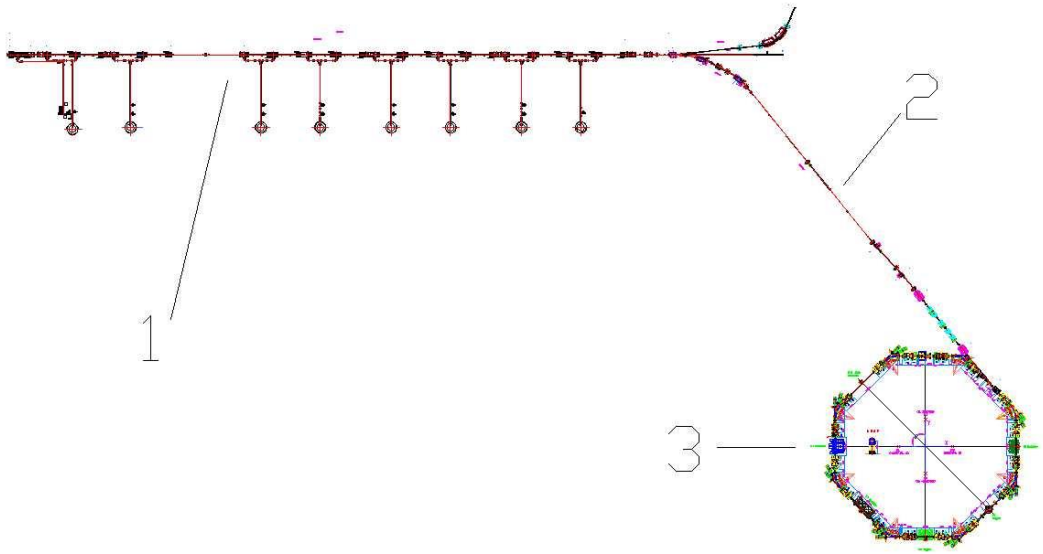
# Ⅰ Introduction

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), it was designed to deliver world-leading intensity and brightness light.




1-Linac

2-Transport

3-Storage Ring

The primary control network has **two important functions:**

(1) Making sure the relative relationship of linac and synchrotron ring;

(2) Restraining the cumulative error of local control network.

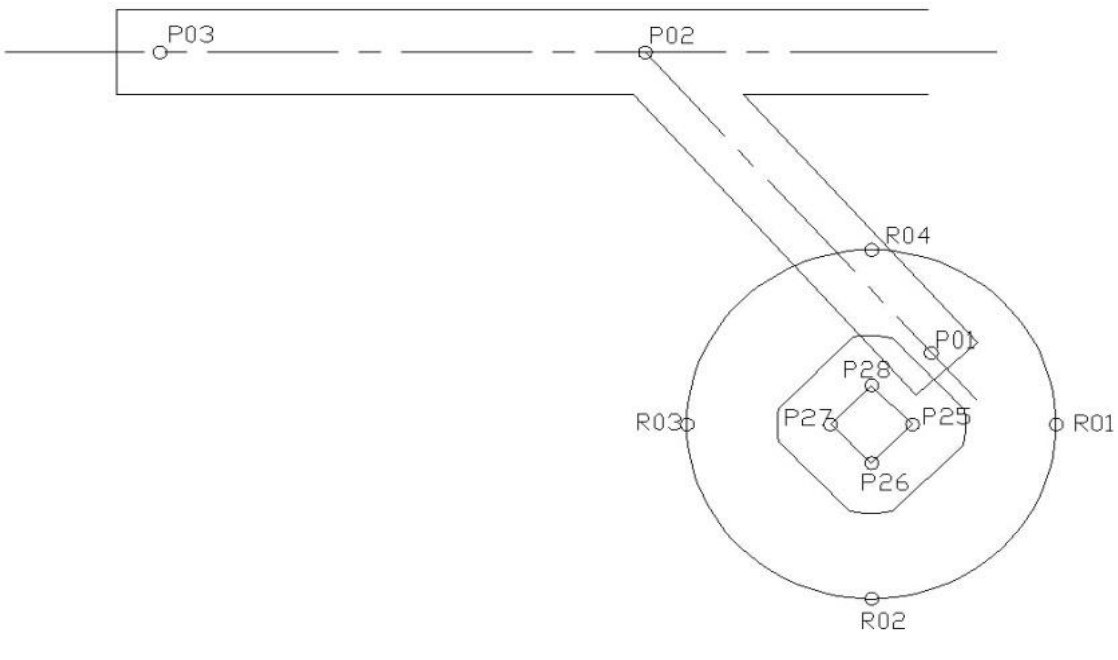
# Contents

- Project design
- Optimal design
- Actual measuring
- Adjustment and Accuracy assessment

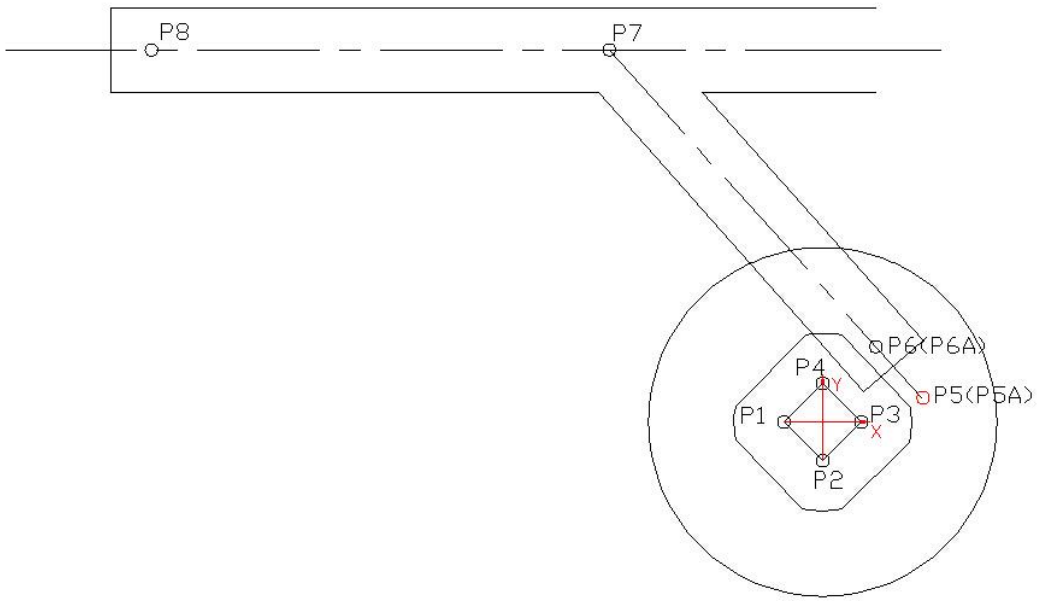
# Ⅱ Project design of the primary control network

Based on the structure characteristic of HLSⅡ, by consulting the design methods of other particle accelerators, triangulateration network is considered to be suitable.

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 datum points of initial building of Hefei light source are absolute reference all the time.




In the process of the upgrade, because of the influence of the obstruction and other reasons, some points can't be observed directly. By using the more advanced instruments, the original primary control network was simplified.

# Ⅲ Optimal design of primary control network

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

$$\min\left\{Z\left(x\right)\right\}$$

$$g_i\left(x\right)\le 0 \quad \text{i=1, 2, 3,}\cdots$$

$$h_i\left(x\right)=0 \quad \text{j}=1, 2, 3,\cdots$$

$Z\left(x\right)$ is objective function

$g_i\left(x\right)\le 0$ is inequality constrain

$h_i\left(x\right)=0$ is equality constrain

$\chi$ is design variable.

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

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

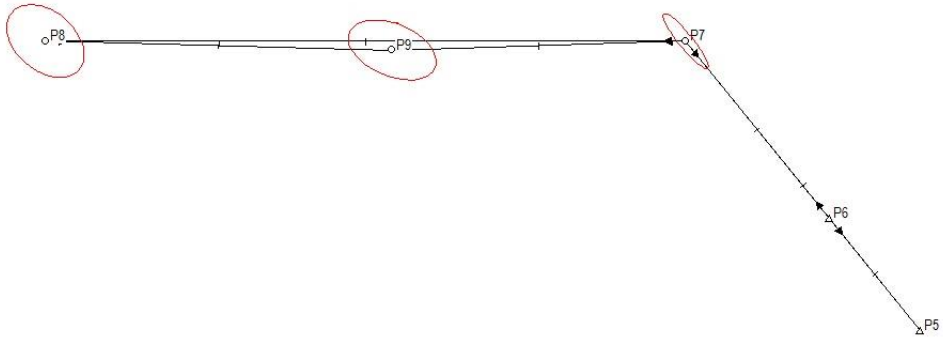
Optimal design of control network is divided into **four categories**, the optimal design of the HLSⅡ primary control network is **third category**: improving design; fixed parameter $Q_x$ , A and P are undetermined by parameters. On the base of the primary control network, designing the new points, and adding new observed values to meet the requirement of $Q_x$

According to the design experience of control network and the observation of drawing design, P8 is possibly the weakest point and the ranging of P7P8 is weakest ranging.

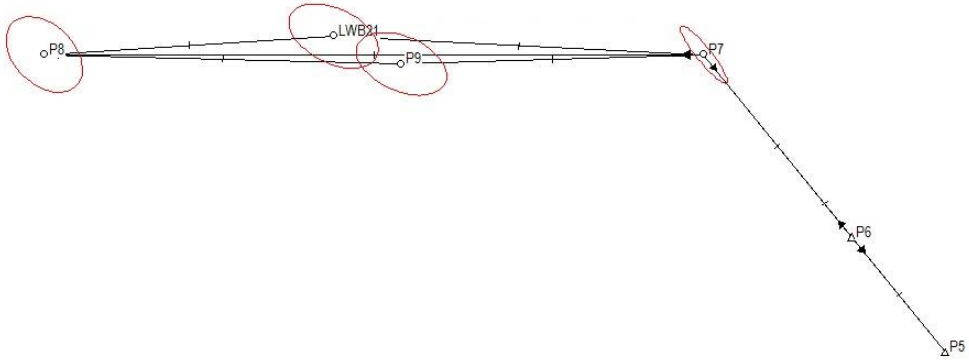
Simulation method of Monte-Carlo is used to simulate a set of observation data and making a series of simulation experiences. According to the fact of HLSⅡ, adding one or two points between the P7 and P8, calculating and obtaining three different results about P8

| 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, by comparing the error of P8 of different design plans, the accuracy of P8 that adding two points P9 and P10 enhances 10% than without adding points. the third plan is elected to be the final plan.

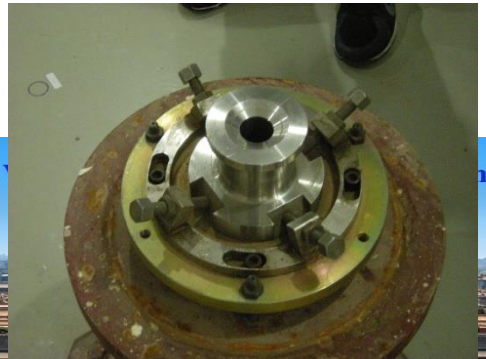

Final Plan




# Ⅳ The actual measuring of the primary control network

## A. The structure design and distribution of the network points

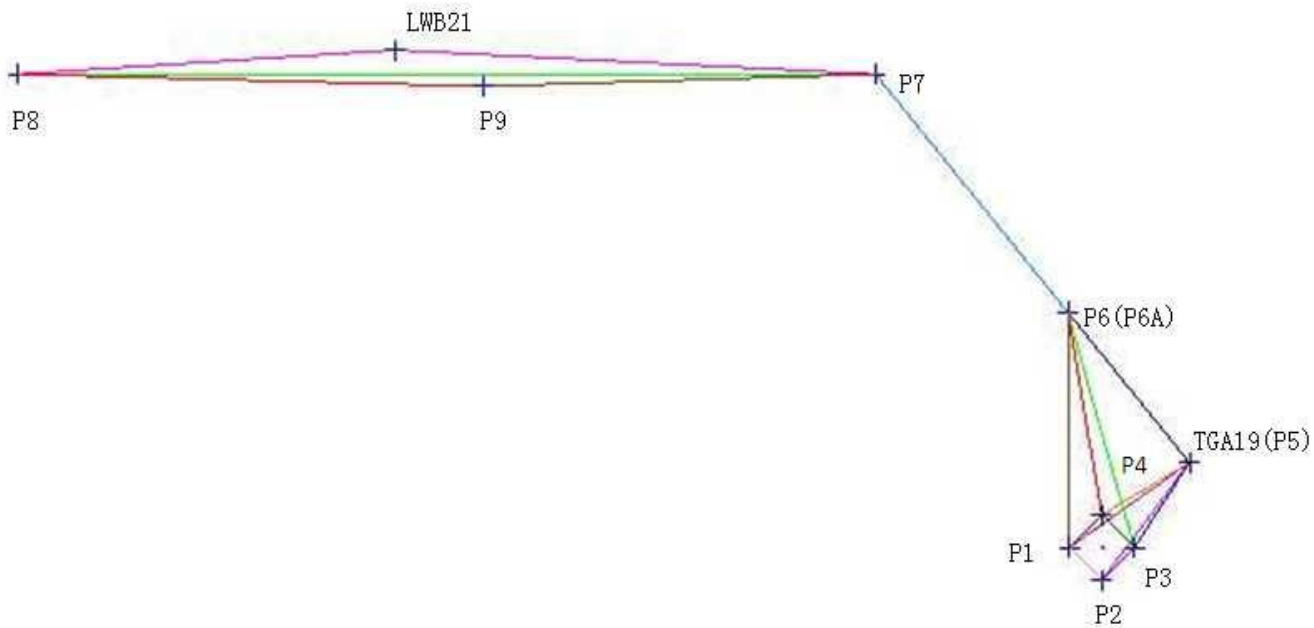
Cone design is adopted to match the Ø 38.1mm target bar, the bar diameter of different instruments are same, it benefits to exchange. because of the error of machining, there actually are three touching points, and the positional repeatability is better than 0.01mm.

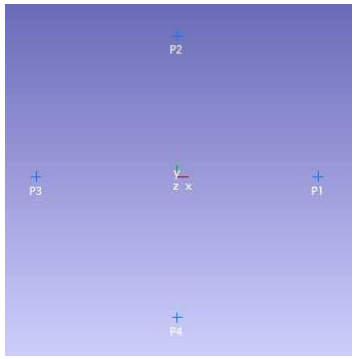
# B. Instruments and software

The model of laser tracker is Leica LTD840, the total station is TDA5005, the plummet is NL. The range accuracy of laser tracker is ± 0.03mm, and angular resolution is better than 0.2″. The angular accuracy of total station is ±0.5″, the range accuracy is 0.5mm in the range of 200m. The plummet can offers a high-accuracy perpendicular, the accuracy of it is 1:200000

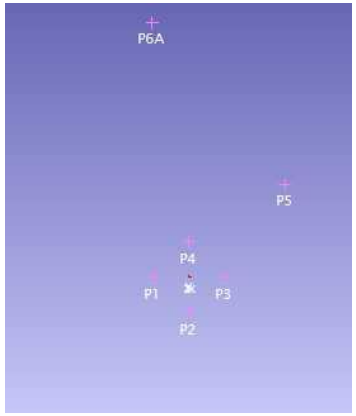

# C. Actual measuring



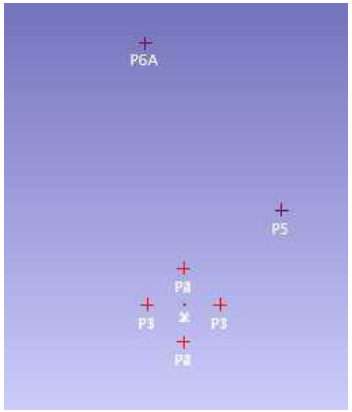

(1)Plummet is used to project the points TGA19 and P6 , naming them P5 and P6A, and building a coordinate system bases on P1-P4,




Theoretical value of P1-P4




Best-fit




Actual value of P1-P4 and P5, P6A

(2)Using the level and laser tracker to measure the P1-P4 and adjust them, the actual position of P1-P4 was similar to the theory, then using the laser tracker to measure the P1-P4, P5 and P6A. Best-fit is used and the coordinate value of. P5 and P6A can be obtained, so the TGA19 and P6 is also obtained.

(3) Finally, total station is positioned at the points TGA19,P6,P7,P8 to measure the range and angle.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# Ⅳ Adjustment and accuracy assessment

Analyzing the measurement data after actual measuring, then making a indirect adjustment and accuracy assessment.

## A. Indirect adjustment

The error function of ranging measurement:

$$\mathrm{v}_{\mathrm{ij}} = -\frac{\Delta X^0}{S^0}\hat{x}_i - \frac{\Delta Y^0}{S^0}\hat{y}_i + \frac{\Delta X^0}{S^0}\hat{x}_j + \frac{\Delta Y^0}{S^0}\hat{y}_j S^0 - l \qquad (1)$$

$$l = L - S^0$$

The error function of angle measurement：

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

$$l = L_i - (\alpha_{ij}^0 - \alpha_{ik}^0) = L_i - L_i^0 \qquad (2)$$

The observation value of HLSⅡ has nine angle measurements and eight range measurements, 17 error functions were obtained, necessary observations are t=2 ×4=8. The adjustment value of undetermined 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 according to the incremental formula

| 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 |

| 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 range and angle，the RMS of unit weight is $\sigma_0 = 0.5''$, the angle weight is

$$P_{\beta_I} = \frac{\sigma_0^2}{\sigma_\beta^2} \qquad (3)$$

the range weight is

$$P_{S_I} = \frac{\sigma_0^2}{\sigma_{S_I}^2} \qquad (4)$$

Because of the accuracy index of TDA5005 is known，and according to the formula (3) and (4)，so weight matrix 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(1) and (2), B matrix and $l$ matrix can be obtained

$$B_{17\times 8}=\begin{bmatrix} -0.7772,0.6292,0,0,0,0,0,0 \\ -0.7768,0.6296,0,0,0,0,0,0 \\ 0.305,0.999,0,0,-0.0305,-0.9999,0,0 \\ \vdots \\ 0,0,0,0,0.0638,-0.9979,-0.6385,0.9979 \\ \vdots \\ 0,0,-0.3743,5.8465,0,0,0.3742,-0.5464 \end{bmatrix}$$

$$l_{1\times 17}=\left[-0.996315,-0.114728,-2.012124\cdots-8.022675,-0.177201\right]^{T}$$

error function：

$$V = B\hat{x} - l \qquad (5)$$

According to the least squares method, $\hat{x}$ is match to $V^T PV = \min$ , transposition:

$$B^T PV = 0 \qquad (6)$$

The unknown number of the formula of（5）and（6）are 17 and 8，the number of the functions are 25，unique solution. Canceling $V$ ：

$$B^T PB\hat{x} - B^T Pl = 0 \qquad (7)$$

and

$$N_{BB} = B^T PB,\ \ W = B^T Pl \qquad (8)$$

simplify（7），obtaining the normal equation

$$N_{BB}\hat{x} - W = 0 \qquad (9)$$

$N_{BB}$ is non-singular matrix, $\hat{x}$ has unique solution

$$\hat{x} = N_{BB}^{-1} W = (B^T P B)^{-1} B^T P l \qquad (10)$$

Put $B, P, l$ into the formula (10)：

$$\hat{x} = \left[-0.342, 0.897, -1.091, 0.885, -0.307, -6.931, 0.936, 0.72\right]^T \quad (mm)$$

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

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

## B. Accuracy assessment

The actual RMS of unit

$$\hat{\sigma}_0 = \sqrt{\frac{V^T P V}{\mathrm{r}}} = 0.4498'' \qquad (11)$$

According to the inverse matrix of weight $N_{BB}^{-1}$ ,error of every undetermined points：

$$\hat{\sigma}_{P7} = \hat{\sigma}_0 \sqrt{Q_{X_{P7}} + Q_{Y_{P7}}} = 0.61$$

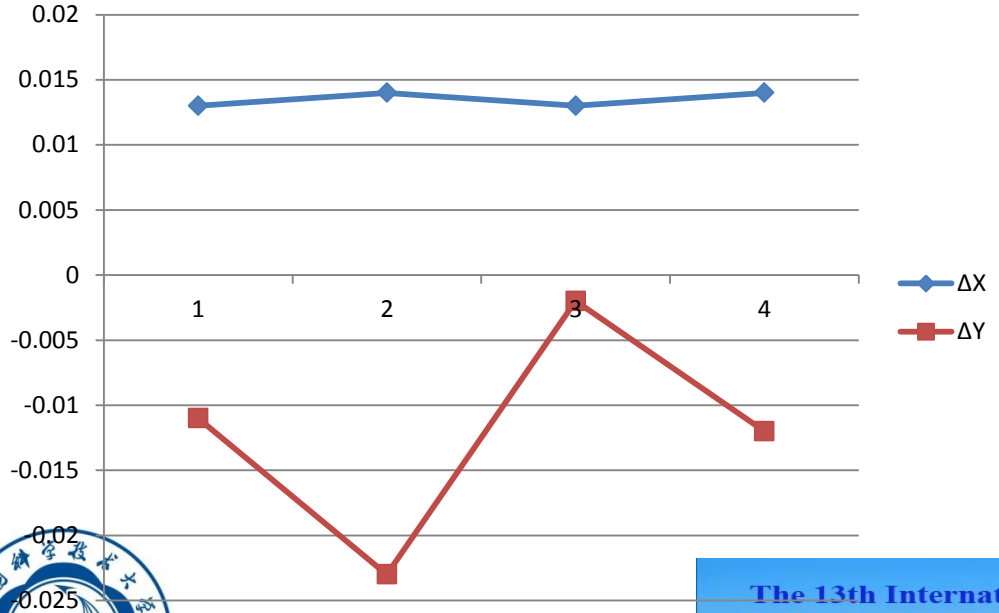
$$\hat{\sigma}_{P8} = \hat{\sigma}_0 \sqrt{Q_{X_{P8}} + Q_{Y_{P8}}} = 0.87 \qquad (12)$$

$$\hat{\sigma}_{P9} = \hat{\sigma}_0 \sqrt{Q_{X_{P9}} + Q_{Y_{P9}}} = 0.91$$

$$\hat{\sigma}_{LWB21} = \hat{\sigma}_0 \sqrt{Q_{X_{LWB21}} + Q_{Y_{LWB21}}} = 0.91$$

# 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.




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

# Ⅵ **Conclusion**

The project of HLSⅡ is successful; indirect adjustment is used to adjust the measuring data, the accuracy of the primary control network meets 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 successfully obtained, and it also proves the success of the upgrade project.

# THANK YOU


The 13th International Workshop on Accelerator Alignment(IWAA2014)
October 13-17, 2014
IHEP, Beijing, China

# Why I calculate the primary control network by hand computation?

My major is not the geodesy or survey, now I study the alignment of accelerator, I think the ability of programming of adjustment is necessary. In order to master the ability that writing a program accord to the fact, knowing the process of adjustment is necessary.