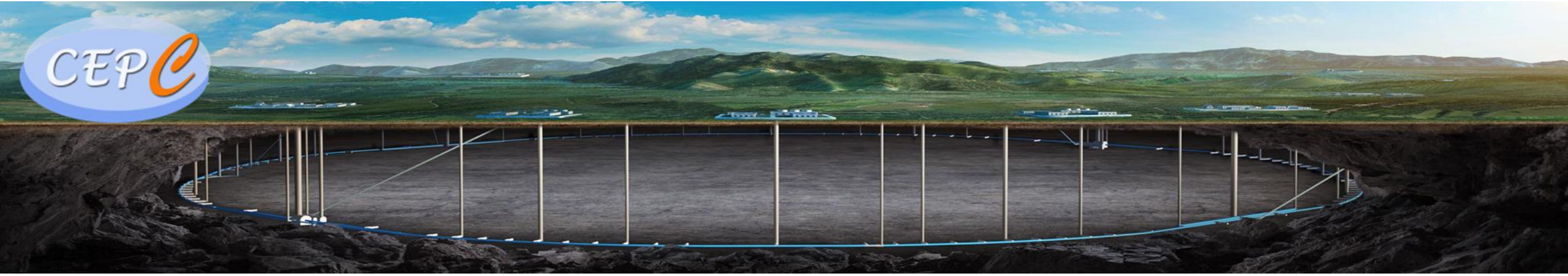

CEPC control survey scheme

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Institute of High Energy Physics (IHEP)

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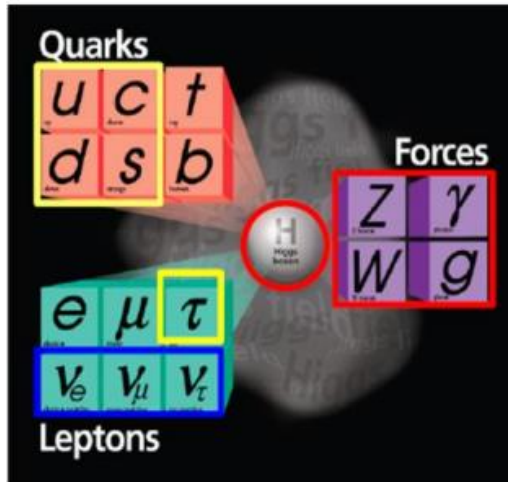
Oct. 7-12, 2024, SLAC USA

Contents

1、Introduction

- The Circular Electron Positron Collider (CEPC) is a large international scientific facility proposed by the Chinese particle physics community in 2012 for Higgs studies.



- CEPC covers the energy from Z to ttbar, with the priority operation for Higgs.

Parameter		Operation mode			
		H	Z	W	$t\bar{t}$
Colliding particles		e^+, e^-			
No. of interaction points		2			
Center-of-mass energy (GeV)		240	91	160	360
Luminosity (10^{34} $cm^{-2}s^{-1}$)	30 MW	5	115	16	0.5
	50 MW	8.3	192	27	0.8

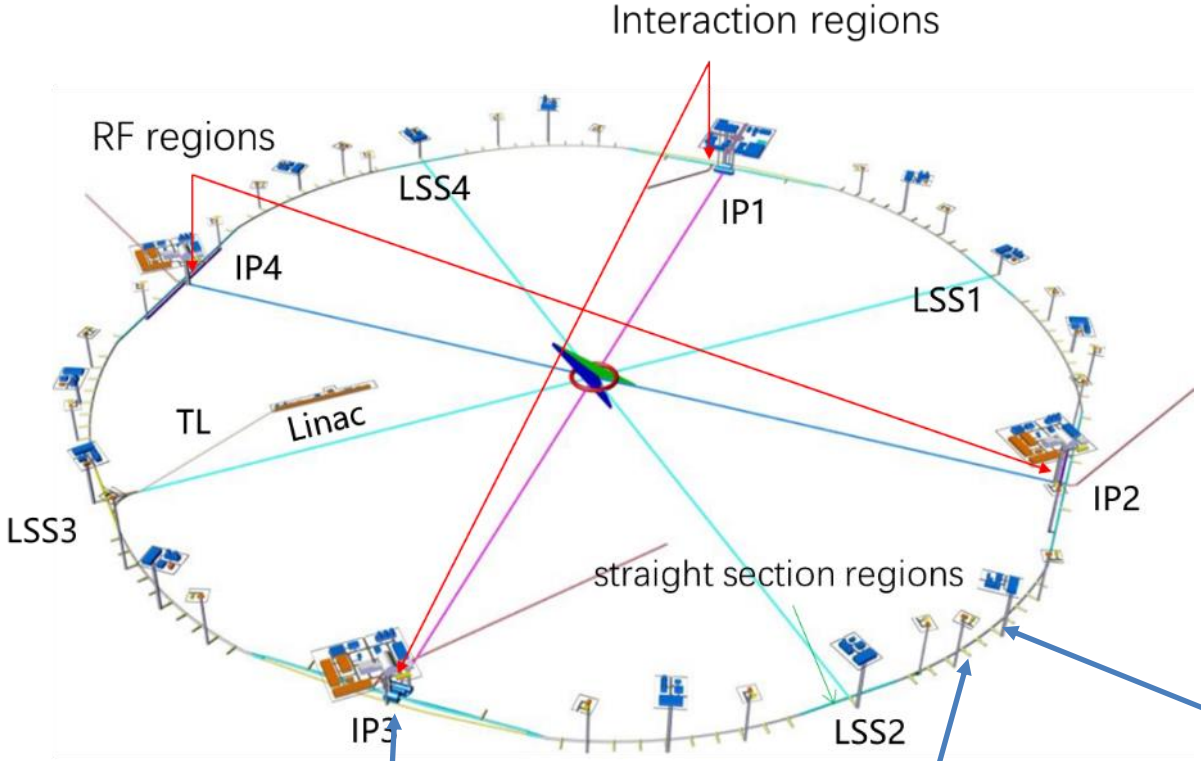
Operation Plan

Particle	Years	SR Power (MW)	Total no. of events
H	10	50	4.3×10^6
		30	2.6×10^6
Z	2	50	4.1×10^{12}
		30	2.5×10^{12}
W	1	50	2.1×10^8
		30	1.3×10^8
$t\bar{t}$	5	50	0.6×10^6
		30	0.4×10^6

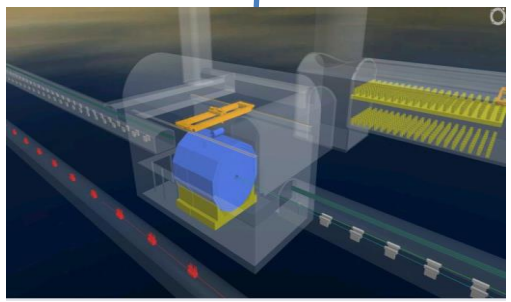
Construct the Super Proton-Proton Collider (SPPC~125TeV), to explore new particle physics through various collision modes.

1、Introduction

Machine Layout

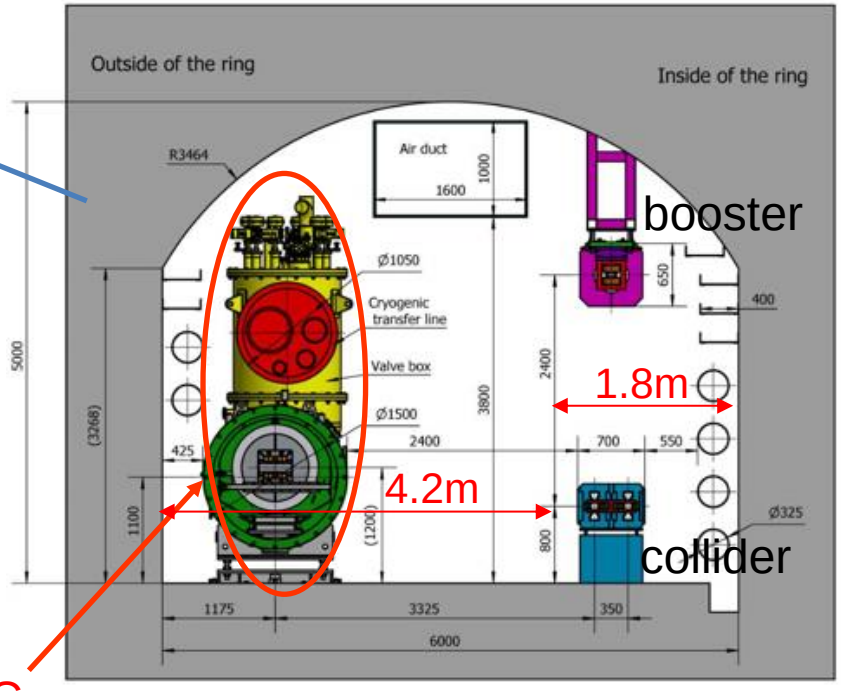


Linac: 1.8km
TL:1.5km
Circumference of ring tunnel:100km
Collider: 100km
Booster: 100km
Tunnel cross section: 6X5m



Interaction region

Ring tunnel



Tunnel cross section

CEPC TDR Accelerator System Parameters

Linac

Parameter	Symbol	Unit	Baseline
Energy	E_{e^-}/E_{e^+}	GeV	30
Repetition rate	f_{rep}	Hz	100
Bunch number per pulse			1 or 2
Bunch charge		nC	1.5 (3)
Energy spread	σ_E		1.5×10^{-3}
Emittance	ε_r	nm	6.5

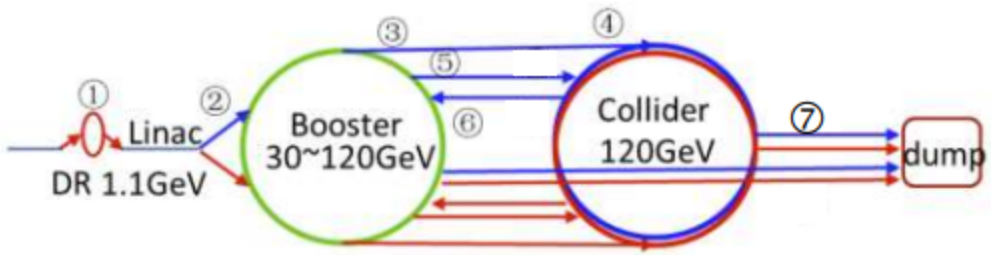
Booster

		tt	*H*		*W*	*Z*	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
Circumfer.	km	100					
Injection energy	GeV	30					
Extraction energy	GeV	180	120		80	45.5	
Bunch number		35	268	261+7	1297	3978	5967
Maximum bunch charge	nC	0.99	0.7	20.3	0.73	0.8	0.81
Beam current	mA	0.11	0.94	0.98	2.85	9.5	14.4
SR power	MW	0.93	0.94	1.66	0.94	0.323	0.49
Emittance	nm	2.83	1.26		0.56	0.19	
RF frequency	GHz	1.3					
RF voltage	GV	9.7	2.17		0.87	0.46	
Full injection from empty	h	0.1	0.14	0.16	0.27	1.8	0.8

Collider

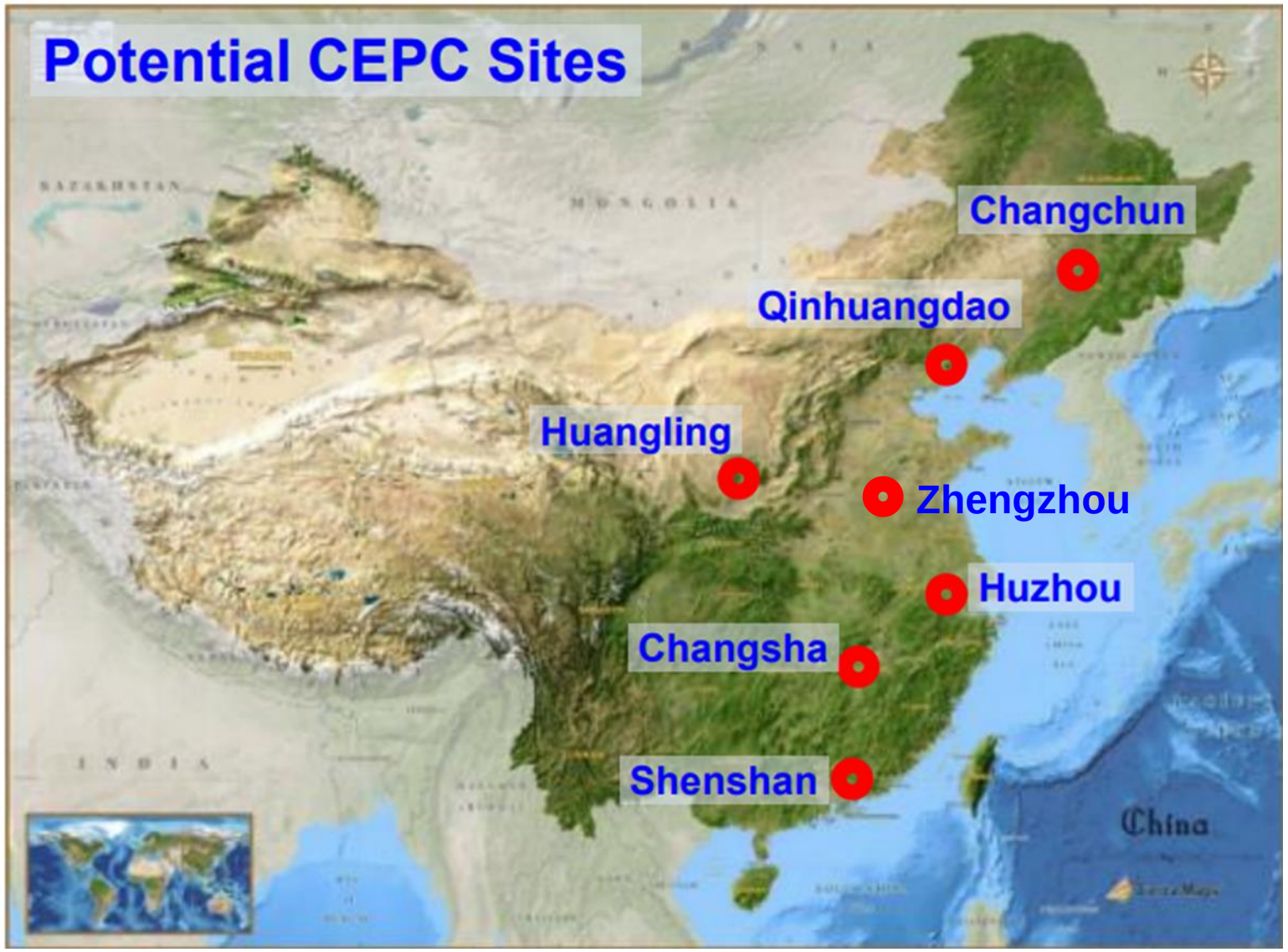
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Energy (GeV)	**120**	**45.5**	**80**	**180**
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**

Transport line



1. Injection/Extraction to the Damping ring (e^+)
2. Injection to the Booster ring from Linac (e^+/e^-)
3. Booster ring extraction system (e+/e-)
4. Collider off-axis injection system (e+/e-)
5. collider on-axis swap-out injection (e+/e-)
6. Collider swap-out extraction (e+/e-)
7. beam dump system (e+/e-)

1、Introduction

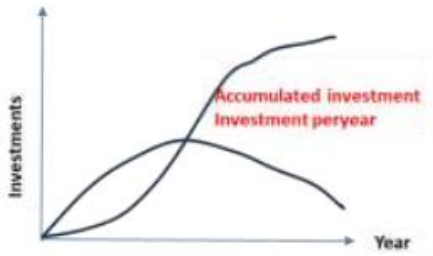


- Consideration factors: geological conditions, environment, economic, transportation, power supply and the level of support from the local government .
- Site selection will be completed in 2025.

CEPC Milestones, Timeline and Human Resources

Year	2012	2013	2015	2017	2018	2023	2025	2027	2030	2035
Human resources (TFE)			~50		~100	~200	~300	~500	~2800	~2500

Year	Accelerator human resource	Accumulated accelerator spending Billion RMB
2015	50	-
2018	100	-
2023	200	0.2
2025	300	0.3
2027	500	0.4
2031	2800	9
2035	2500	20



CEPC kickoff meeting in Sept. 2013

CEPC detector reference design
Will be completed by June 2025

2025

Proposal (2025) for CEPC entering 15th five year plan

36.4B RMB
Total construction

CEPC EDR site study and civil engineering design

2012.9	2013.9	2015.3	2017.4	2018.11	2023.12	2024 ~ 2027	~2035
CEPC proposed		Pre-CDR	Progress report	CDR	TDR	EDR start of construction	Completion

1、Introduction

- Quantity of components

Component	Collider Ring	Booster	Linac, DR, TL	Total
Dipole	16258	14866	135	31259
Quadrupole	4148	3458	714	8320
Sextupole	3176	100	72	3348
Corrector	7088	2436	275	9799
BPM 、 PR 、 DCCT 、 kicker	3544	2408	180	6132
Septum Magnet	68	32	2	102
Kicker	8	8	2	18
Cryomodule	32	12		44
Electrostatic separator	32			32
Collimator dump	36		8	44
Superconducting Magnets	4			4
Solenoid			37	37
Accelerating structure			577	577
Cavity			4	4
Electron Source			1	1
Positron Source			1	1
Detector	2			2
Total	34396	23320	2008	59724

1、Introduction

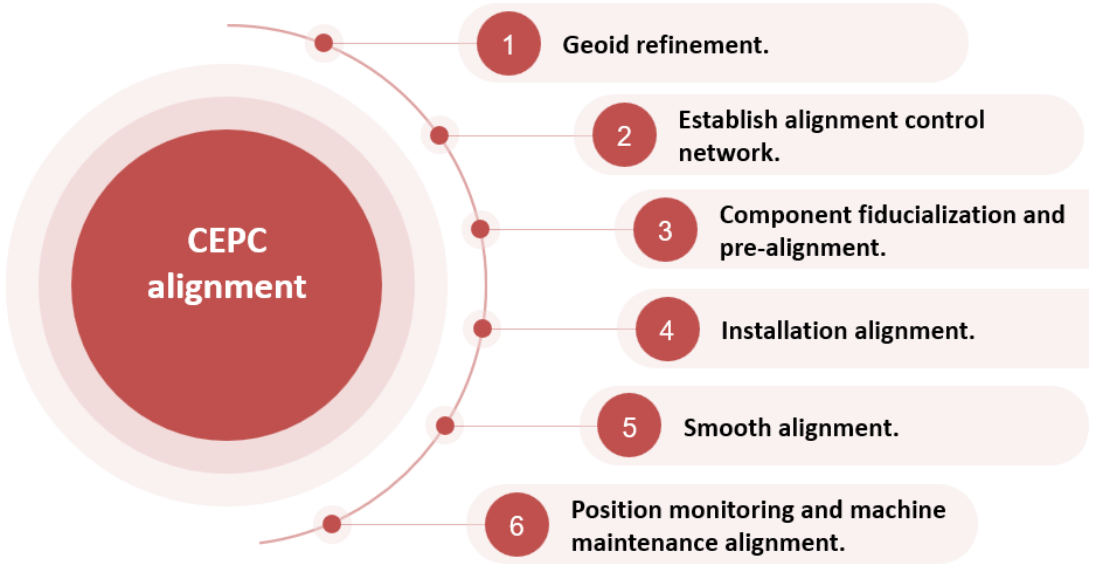
- Goal: Realize the relative position accuracy requirement of adjacent components under a global absolute position control and provide a smooth orbit for beam operation.
- Alignment accuracy requirement

Relative position accuracy requirement of adjacent components（1 σ）						
Component	Transversal /mm	Vertical /mm	Longitudinal /mm	Roll /mrad	Pitch /mrad	Yaw /mrad
Dipole	0.1	0.1	0.15	0.1	0.2	0.2
Quadrupole	0.1	0.1	0.15	0.2	0.2	0.2
Sextupole	0.1	0.1	0.15	0.2	0.2	0.2
Corrector	0.2	0.2	0.3	0.2	0.2	0.2
BPM	0.2	0.2	0.3	0.2	0.2	0.2
Cryomodule	0.5	0.5	1	0.3	0.3	0.3
Septum Magnet	0.2	0.2	0.3	0.2	0.2	0.2
Kicker	0.2	0.2	0.3	0.2	0.2	0.2
Electrostatic separator	0.2	0.2	0.3	0.2	0.2	0.2
IR Quadrupole	0.1	0.1		0.1	0.1	0.1

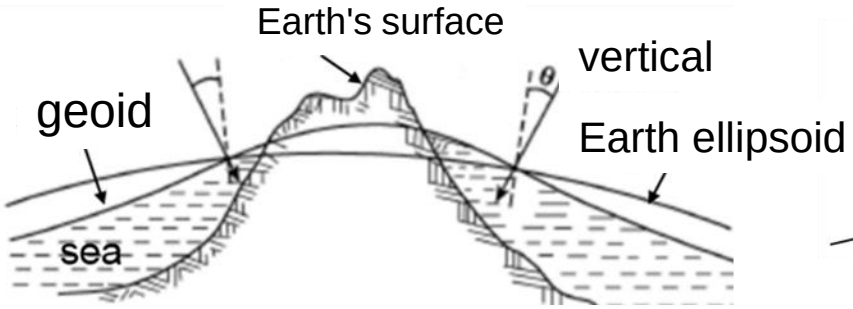
1、Introduction

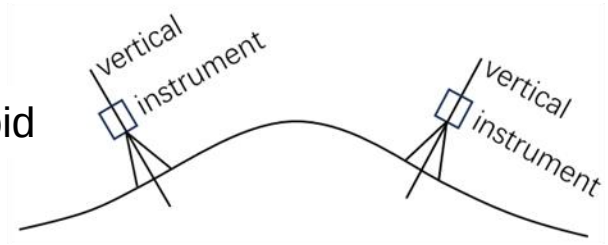
- Technical route of CEPC alignment
  - Build a quasi-geoid model as a global datum for the observations reduction;
  - Establish a control network to provide positional reference framework;
  - By fiducialization and coordinate transformation to calculate the component nominal position;
  - Through initial installation alignment and smooth alignment to meet the final accuracy requirement.

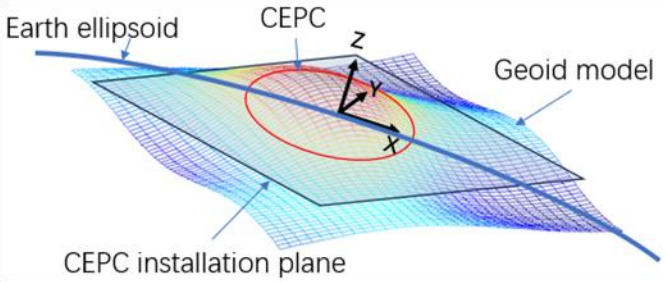
- Key issues of CEPC alignment
  1. High-accuracy control survey of the hundred-kilometer long accelerator.
  2. Component accurate fiducialization.
  3. MDI alignment scheme and technology.
  4. Efficient alignment and installation



2、Geoid refinement





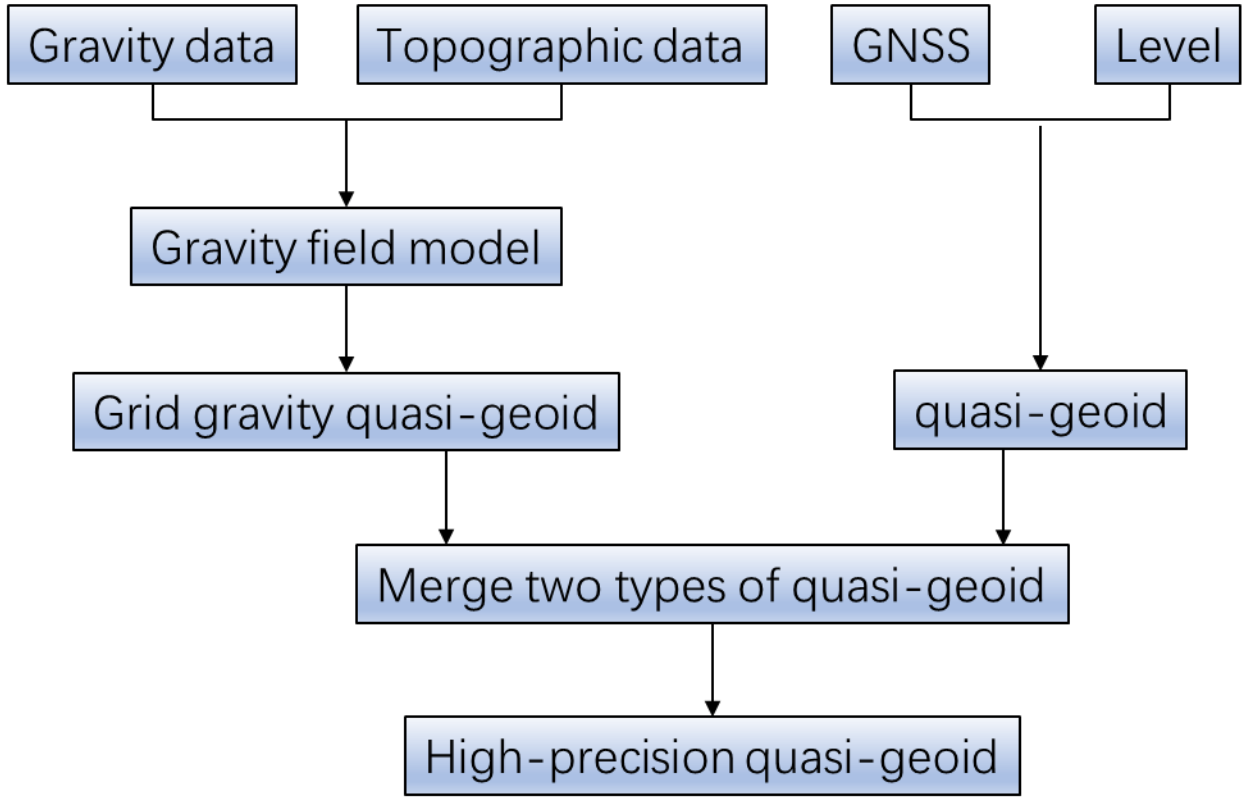


- The measurement reference datum is geoid while the installation reference datum is CEPC XY plane, it is necessary to accurately determine the positional relationship between them by geoid refinement.
- Goal： To build a quasi-geoid model with 10mm elevation anomaly accuracy and 1″ vertical deflection accuracy.

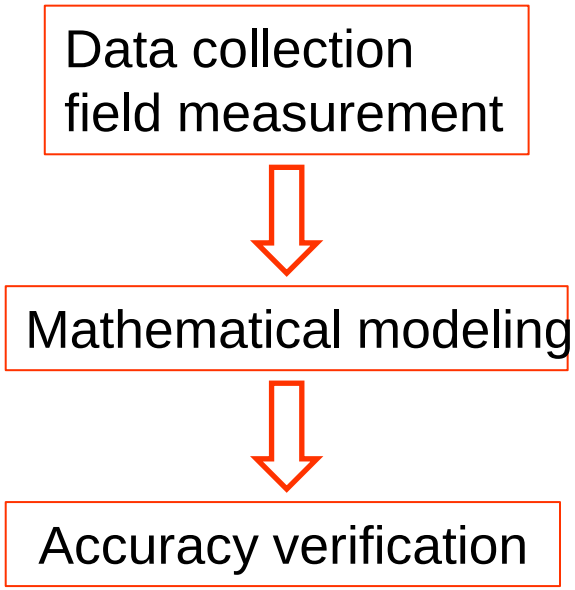
2、Geoid refinement

- Collaborating with Wuhan University a geoid refinement scheme was made.

Geoid refinement scheme

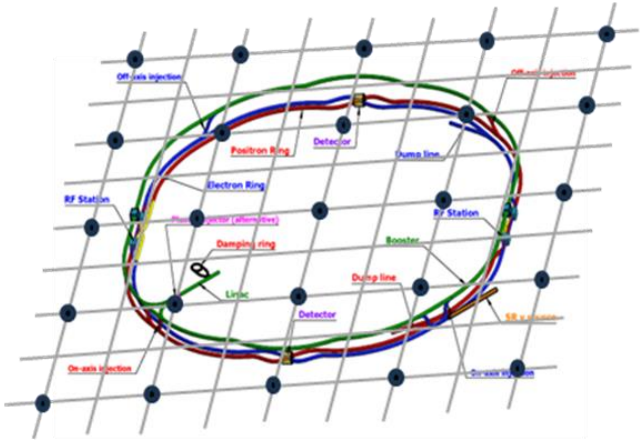


Works need to be done



2、Geoid refinement

- Data collection: Collecting gravity data within a 300km radius of CEPC. Carry out supplementary measurement in areas lacking gravity data.
- Field survey:
  - Build 25 observation points in a range of 32km×32km covering the CEPC area. The observation points will be distributed in a grid pattern with a distance of 5-10km.
  - On each observation point performing GNSS, level, and vertical deflection measurement.



- Mathematical modeling:
  - Using the collected gravity data and EIGEN6C4 according to the Stokes-Helmert method to calculate the gravity quasi-geoid.

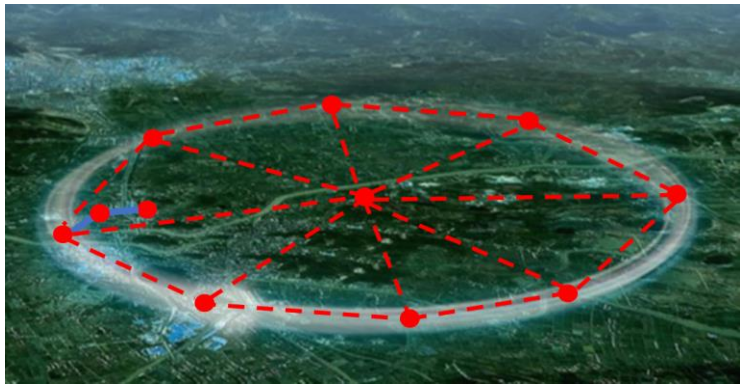
2、Geoid refinement

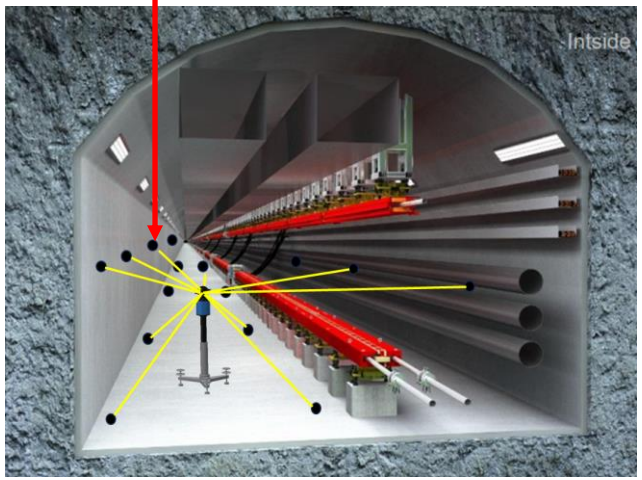
- Using the topographic data SRTM DTM, applying removal-restoration principle, according to Airy-Haiskanen model to do the gravity anomaly topographic equilibrium reduction.
- Applying the second type Helmert agglutination method to calculate the gravity quasi-geoid.
- Using spherical crown harmonization analysis method jointly solve GNSS level, vertical deflection observations and the gravity quasi-geoid, then get the resolution 2’×2’ grid quasi-geoid model.

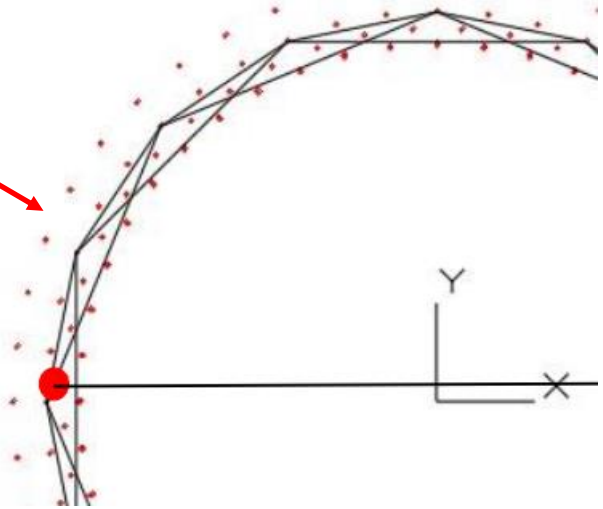
- Next work
  - Model transformation: The quasi-geoid model is based on the ground measurement data and needs to be transferred to the tunnel elevation.
  - geoid refinement experiment

3、Control network establish scheme

- Control network： provide an unified positional reference frame for CEPC alignment and control the error accumulation；
- 3 levels control network
  - Surface control network
  - Backbone control network
  - Tunnel control network

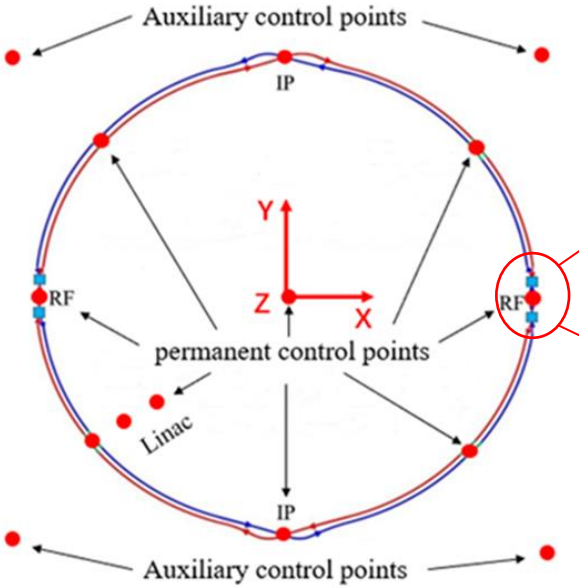


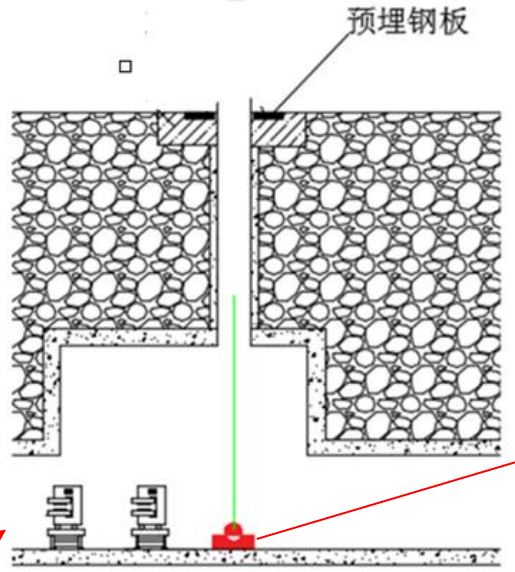




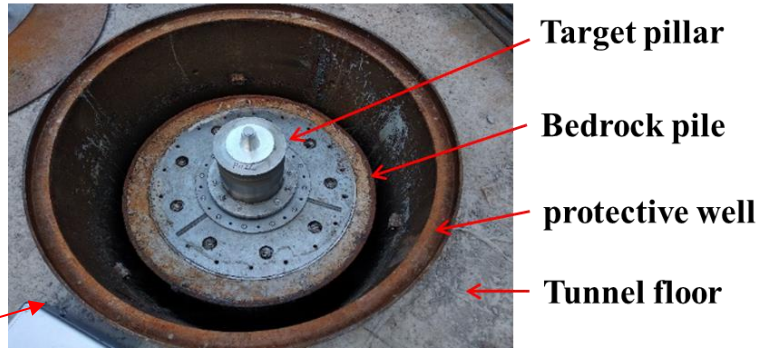
3、Control network establish scheme

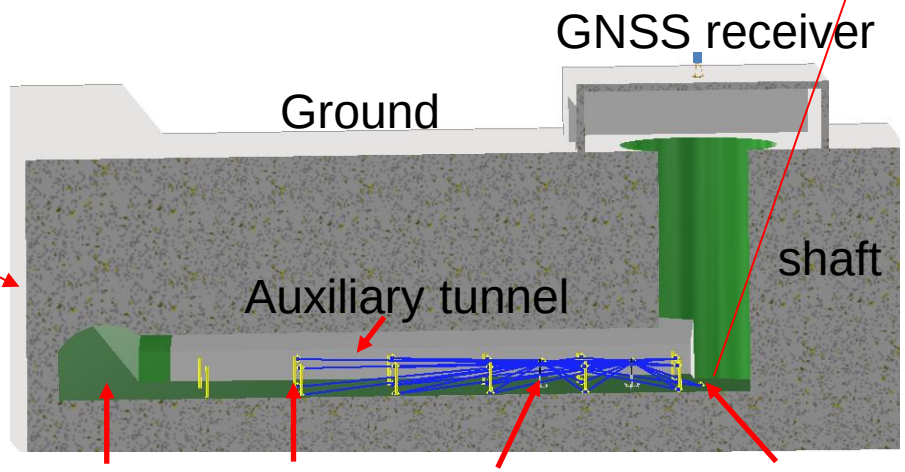
- Surface network structure
  - Ring 8 points + 1 center point +2 linac points + Several auxiliary points.
  - The height from ground to ring tunnel :50~200m.

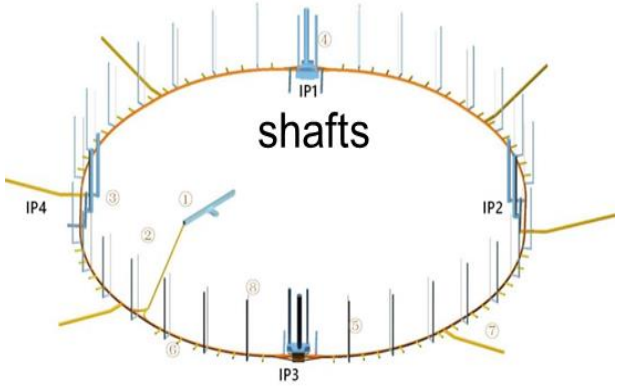




Structure of the permanent point in tunnel







3、Control network establish scheme

- Surface control network measurement:

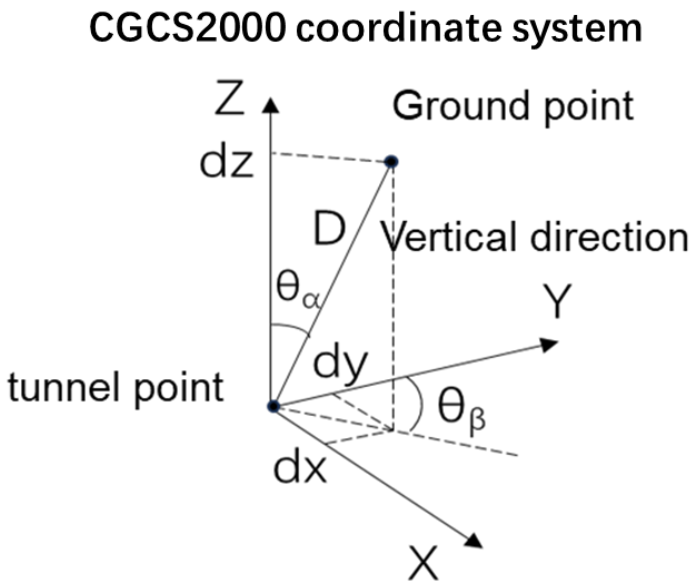
GNSS measurement	
Measuring instrument	GNSS receivers (Leica GS10+AR20)
Group	16×(2 persons)
Software	GAMIT
Time	3 weeks
Accuracy	Horizontal ±5mm, Elevation ±10mm

Leveling	
Measuring instrument	Leica NA2, LS15
Group	4 × (6 persons)
Software	Starnet, CosaLEVEL
Time	4 weeks (4km/group/day)
Accuracy	Better than 7mm

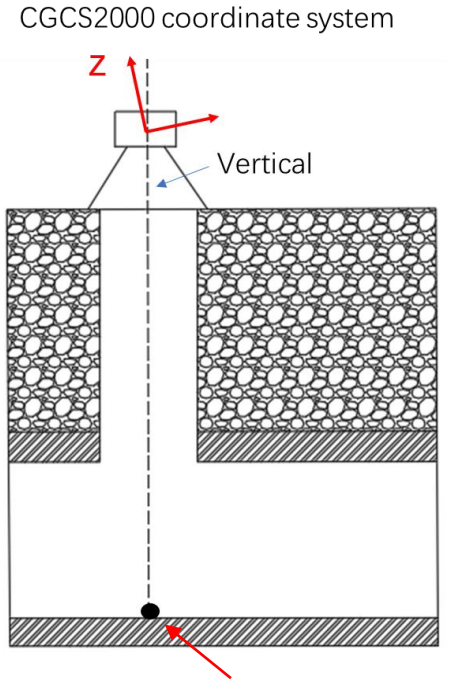
- Surface control network observations processing:
  - GNSS: Using the China Geodetic Coordinate System 2000 (CGCS2000) coordinates of CORS stations around CEPC region as the known data, conducting GNSS observations adjustment to obtain the CGCS2000 coordinates of each point.
  - Leveling: Using the national benchmarks as known points, conducting leveling observations adjustment to obtain the normal height of each point. Using the normal heights and the quasi-geoid model to calculate the geodetic heights based on the CGCS2000 ellipsoid.

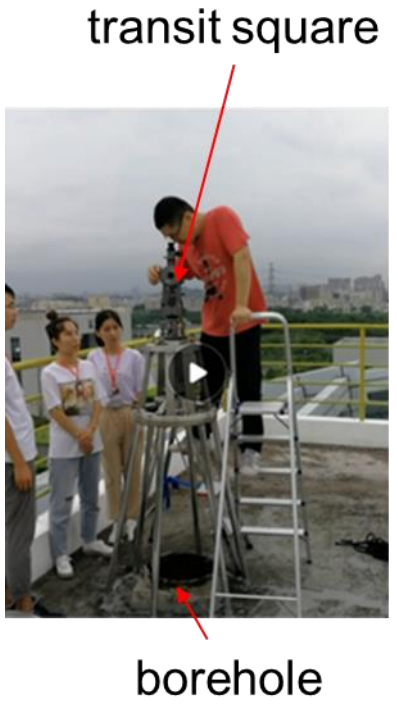
3、Control network establish scheme

- Surface and tunnel connection measurement：①Centering observation method
  - Based on the vertical direction and the distance between the surface and tunnel points, the CGCS2000 coordinate of tunnel point can be calculated.



$$\begin{cases} dx = D\sin\theta_\alpha \cos\theta_\beta \\ dy = D\sin\theta_\alpha \sin\theta_\beta \\ dz = D\cos\theta_\alpha \end{cases}$$

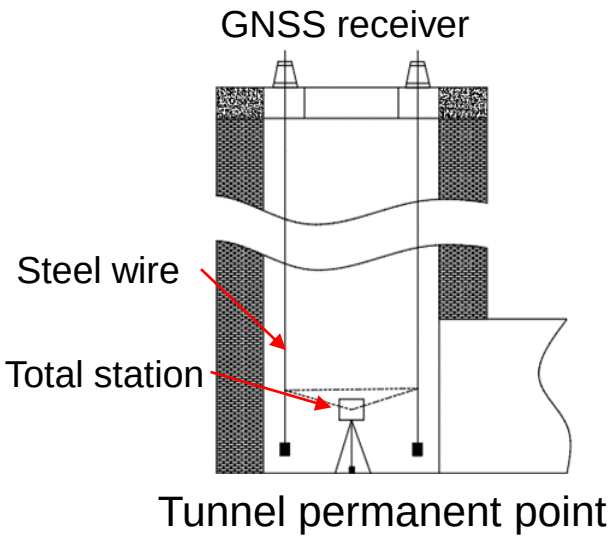


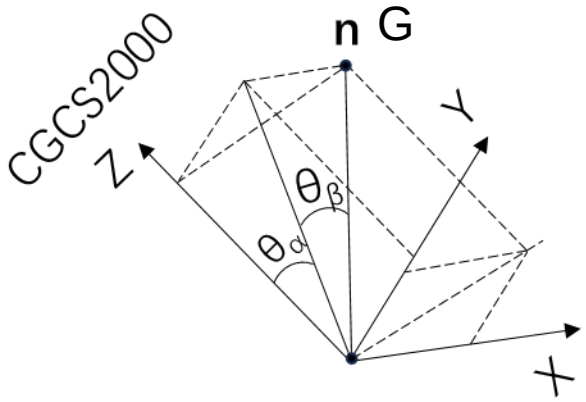


Horizontal error scale: 0.5mm/(100m, 1arcsec.)

3、Control network establish scheme

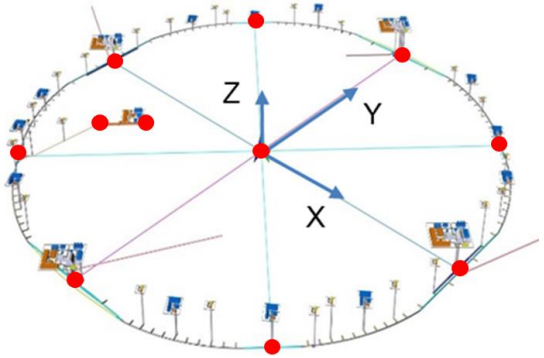
- Surface and tunnel connection measurement：②Single shaft orientation method
  - Set 2 GNSS receivers on the shaft.
  - Hang a steel wire from each surface point to the tunnel.
  - Establish a transitional coordinate system G using the 2 surface points, which elevation direction is same with the vertical. Calculate the coordinates of these 2 surface points in G.
  - Center a total station on the tunnel point, by backward intersection, we can get the horizontal coordinate of this point in G.
  - Based on the distance between the surface and tunnel point to calculate the height value of the tunnel point in G.
  - Calculate back to the CGCS2000 coordinate system from G to obtain the tunnel point coordinate in CGCS2000.

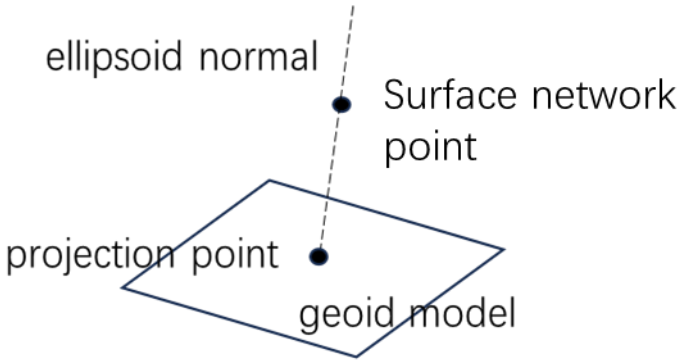


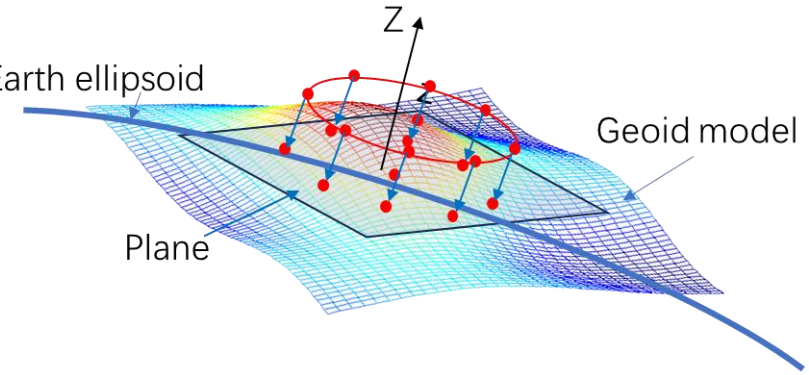


3、Control network establish scheme

- Establish CEPC coordinate system



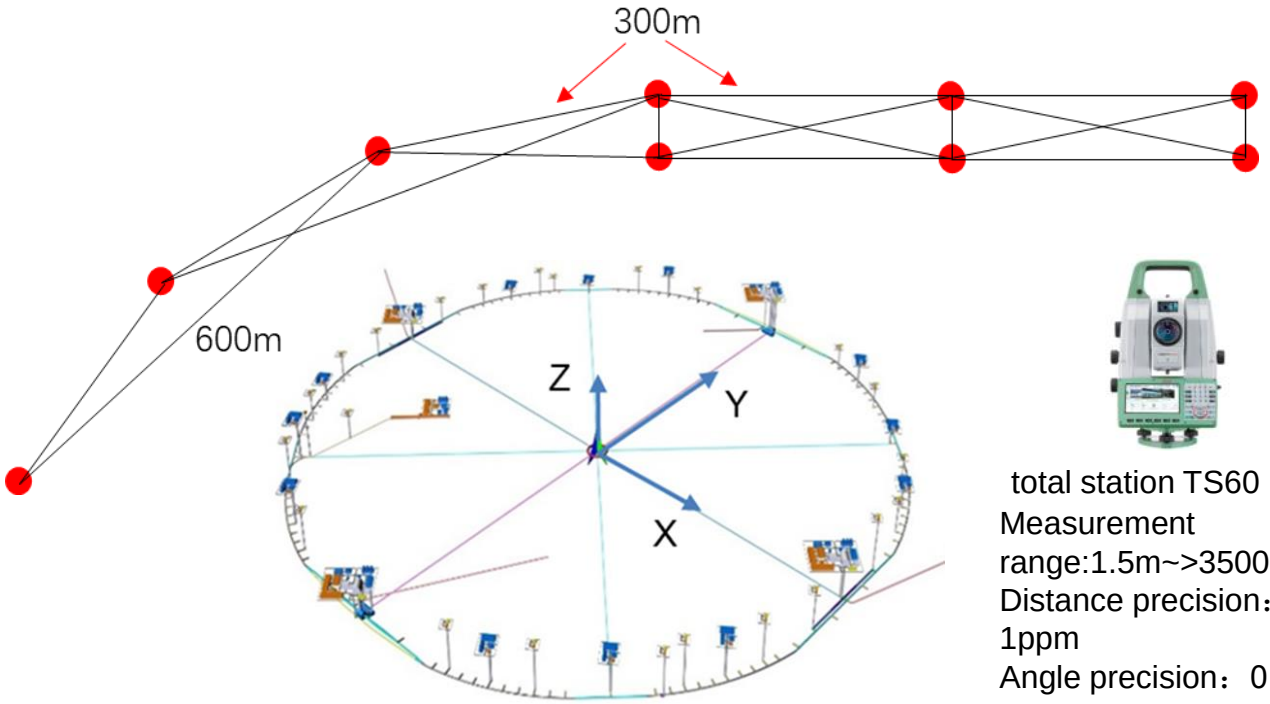




  - Objective: make the XY plane best-fit with the geoid.
    - Projecting the surface control network points onto the quasi-geoid along CGCS2000 ellipsoid normal, fit a plane with these projection points.
  - Establish a transitional coordinate system: Using the ring center point as the origin, the normal of fitting plane as the Z axis, a point to determine the X axis.
  - According to the actual engineering conditions, transform the transitional coordinate system to CEPC coordinate system, the coordinates of surface control network and the transformation parameters between CGCS2000 and CEPC can be obtained.

3、Control network establish scheme

- Backbone control network
  - Function： strengthen the tunnel control network, reduce error accumulation.
  - Built on the ring tunnel floor. Triangulation network in the arc region, quadrilateral network in the straight section region.



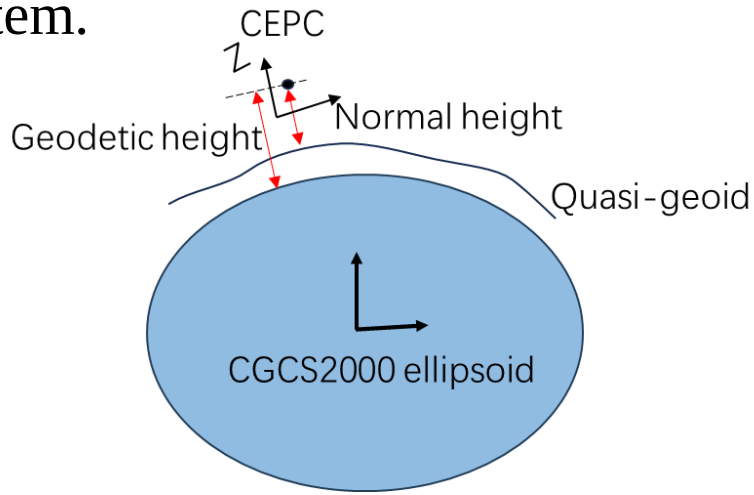
total station TS60
Measurement range:1.5m~>3500m
Distance precision：0.6mm+1ppm
Angle precision：0.5”

3D measurement	
Instrument	Wild NL、Total station、gyro-theodolite
Group	8×(4)
Software	Self-developed
Working day	20 (4points/group/day)

Elevation measurement	
Instrument	Level
Group	8×(4)
Software	COSA、STARNET
Working day	10（2km/group/day）

3、Control network establish scheme

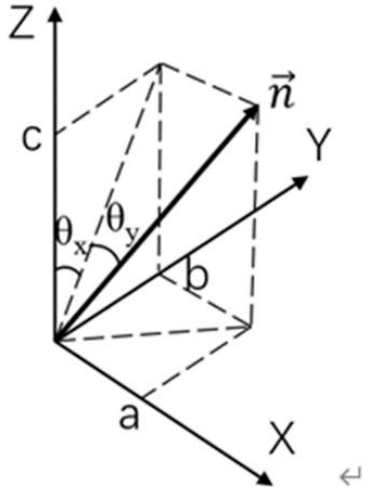
- Backbone control network observations processing scheme：
  - ① Leveling observations：
    - Using the normal heights of the surface control network points as known data to perform a leveling adjustment.
    - Based on the adjustment result, approximate coordinates of the backbone network points and the quasi-geoid model to calculate the geodetic heights of the backbone control network points.
    - According to the transformation parameters between CGCS2000 and CEPC calculate the height coordinates of the backbone control network points in CEPC coordinate system.



3、Control network establish scheme

② Total station observations：

- Based on the approximate coordinates of total station measuring stations and their vertical directions to calculate the elevation axis (Z) direction of each measuring station coordinate system in CEPC coordinate system.
- Using the surface network coordinates and the elevation axis directions of measuring stations as known data, and using the height coordinates of the backbone control network as constraint to perform a 3D adjustment, we can obtain the 3D coordinate of the backbone control network in CEPC coordinate system.



CEPC coordinate system

Vertical vector

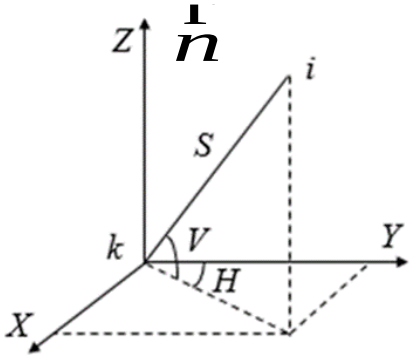
$$\vec{n} = ai + bj + ck$$

θ_x and θ_y in rotation matrix M can be calculated by vertical vector $\vec{n}$

$$\begin{cases} \theta_x = \arctan\dfrac{b}{c} \\ \theta_y = \arctan\dfrac{a}{\sqrt{b^2+c^2}} \end{cases}$$

$$\begin{bmatrix} X_{ki} \\ Y_{ki} \\ Z_{ki} \end{bmatrix} = \boldsymbol{M}\begin{bmatrix} X_i - X_k \\ Y_i - Y_k \\ Z_i - Z_k \end{bmatrix}$$

$$\boldsymbol{M}\left(\theta_{xk} \quad \theta_{yk} \quad \theta_{zk}\right)$$



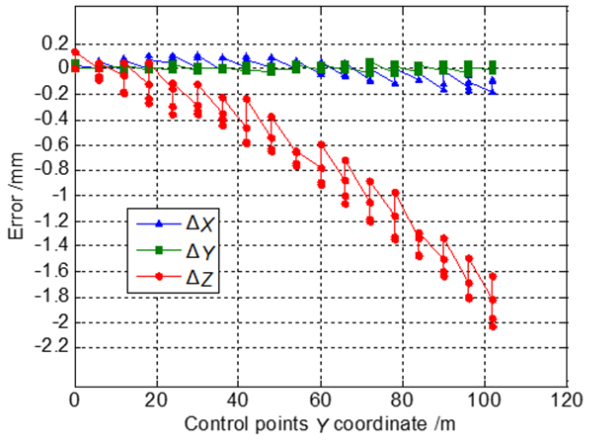
Measuring station coordinate system

Observation equation

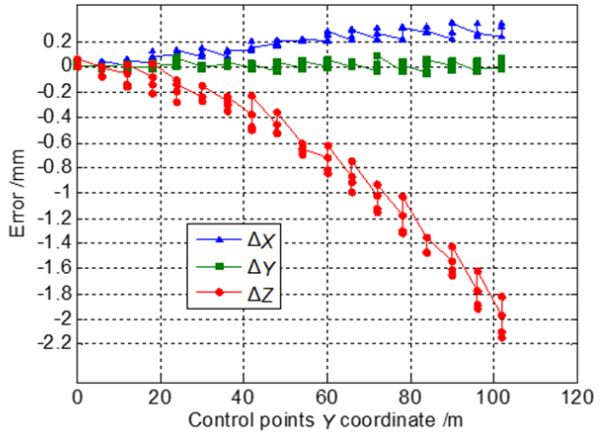
$$\begin{cases} S_{ki} = \sqrt{\bar{X}_{ki}^2 + \bar{Y}_{ki}^2 + \bar{Z}_{ki}^2} + \Delta_{Ski} \\ H_{ki} = \arctan\left(\dfrac{\bar{X}_{ki}}{\bar{Y}_{ki}}\right) + \Delta_{Hki} \\ V_{ki} = \arctan\left(\dfrac{\bar{Z}_{ki}}{\sqrt{\bar{X}_{ki}^2 + \bar{Y}_{ki}^2}}\right) + \Delta_{Vki} \end{cases}$$

3、Control network establish scheme

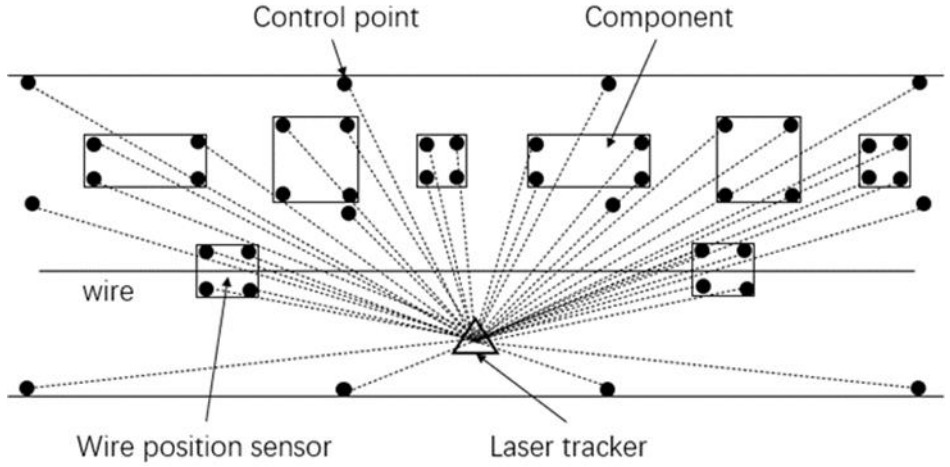
- 3D adjustment software development
  - A 3D adjustment software based on distance and angle observations has been preliminary developed.
  - Advantages: it takes Helmert variance component estimation weighting method， can perform elevation axis-fixed 3D adjustment by input the angel parameters of the elevation axis , can perform adjustment with elevation and line constraints.



3D adjustment program



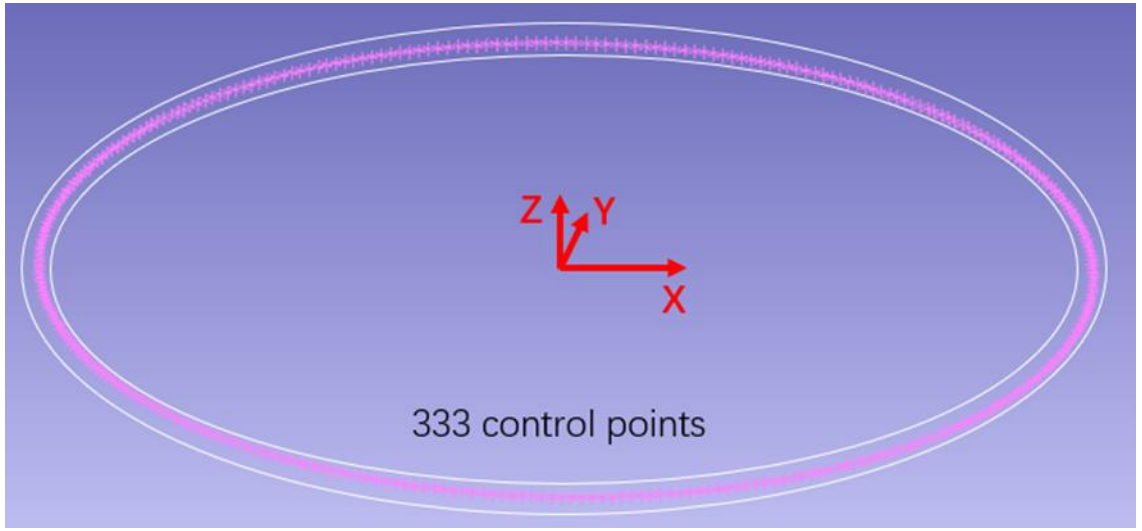
SA



  - Next we will continue to perfect its functions, optimize computation speed and conduct various testing work.

3、Control network establish scheme

- Backbone control network simulation
- Goal:
  a. Analyze the amplitude and trend of control survey errors.
  b. Provide experimental data for the beam orbit alignment error study.
  - The nominal coordinates of the backbone control network were generated.



Simplified to a circular ring with a circumference of 100km.

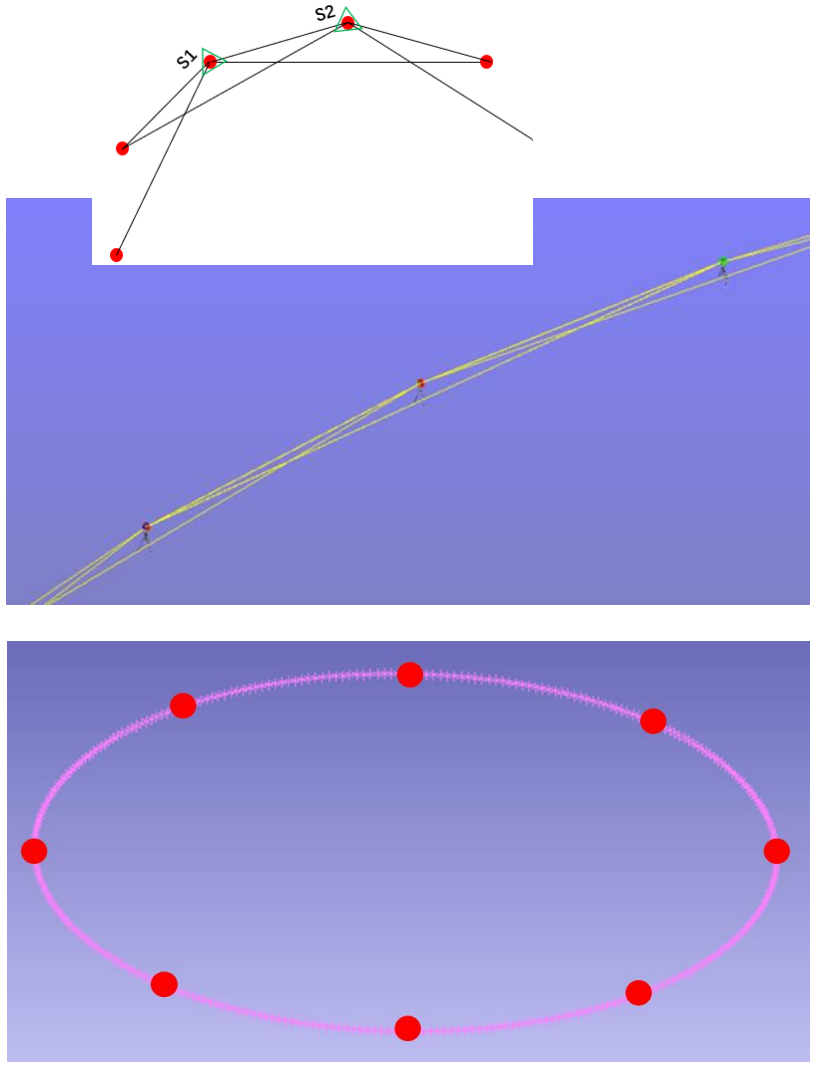
Triangulation network structure.

3、Control network establish scheme

- Generate the simulated observations.

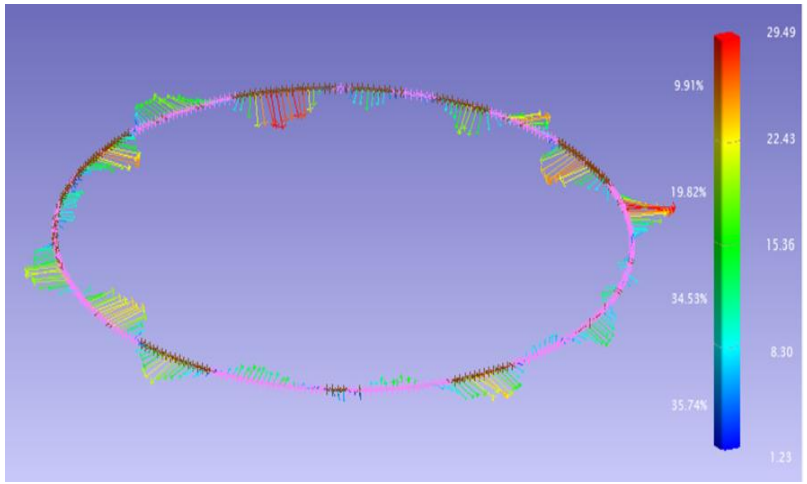
Information of the simulation

Measuring instrument	Total station
Number of stations	333
Observation type	distance and angle
Accuracy of the simulated observations	Distance: 1.5mm+1ppm Azimuth: 1.5”, Zenith:1.5”
Constrained data	8 ring surface network control points. Each point was given a random error of 0-7mm.
Adjustment software	Starnet

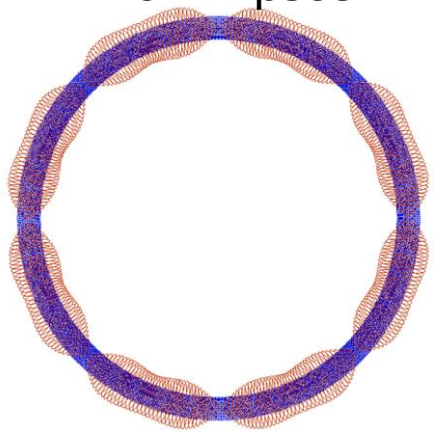


3、Control network establish scheme

- 10 times simulation calculation have been performed.

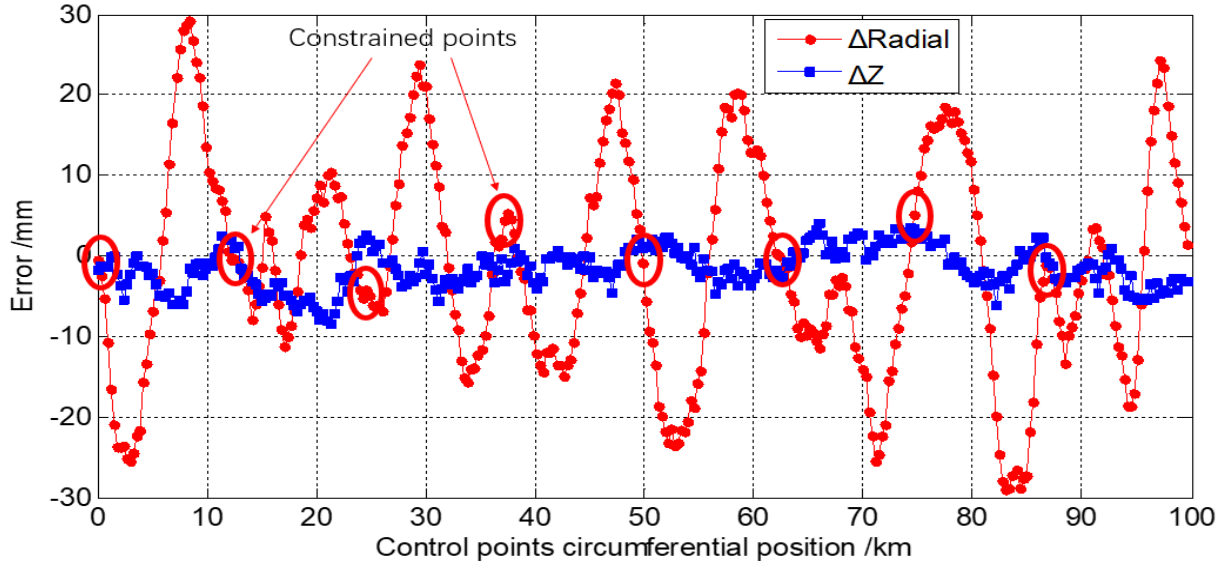


Error Ellipses



Difference between the simulation results and the design values

Error	Radial /mm	Elevation /mm
MAX	29.13~33.5	4.07~8.8
MIN	-38.6~-25.7	-10.4~-5.6
RMS	13.35~10.69	2.8~3.68



Error Ellipses, confidence region 95%(2σ)

Error Propagation	Semi-Major Axis	Semi-Minor Axis
MAX	27.6~29. 6	7.2~7.65
MIN	0	0
RMS	22.79~24.37	4.85~5.1

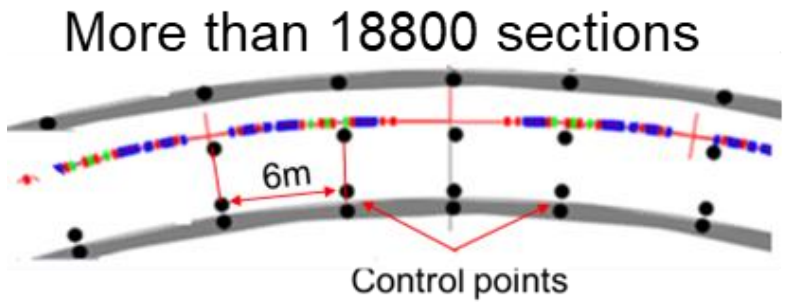
Relative Error Ellipses 95%(2σ)

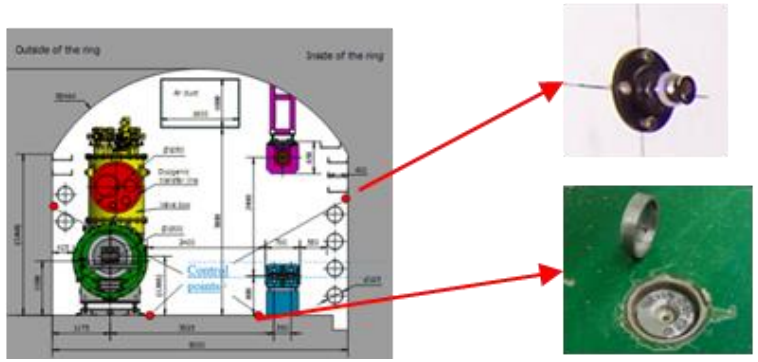
Error Propagation	Semi-Major Axis/mm	Semi-Minor Axis/mm
RMS	5	2

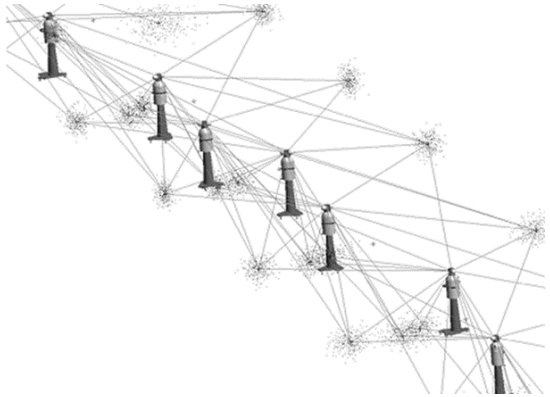
3、Control network establish scheme

- Tunnel control network
  - Provide position reference for component installation and alignment.
- Observations processing
  - Same with backbone control network. Using backbone control network point as known data, perform elevation axis-fixed 3D adjustment.

Tunnel control network measurement	
Instrument	16 laser trackers，8 levels
Personnel	16×(2)
Working month	6
Accuracy	Planar: Standard error 0.35mm(300m) . Relative error 0.065mm(6m) Elevation : Standard error 0.38mm(300m) . Relative error 0.074mm (6m)

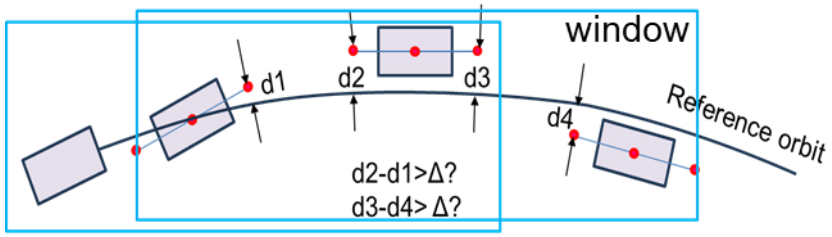






4、Component installation and alignment

- Component installation alignment scheme:
  - Using tunnel control network and laser tracker to perform an initial installation and alignment.
  - Carry out 2 times smooth alignment.

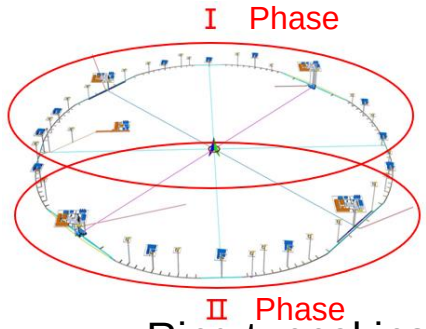


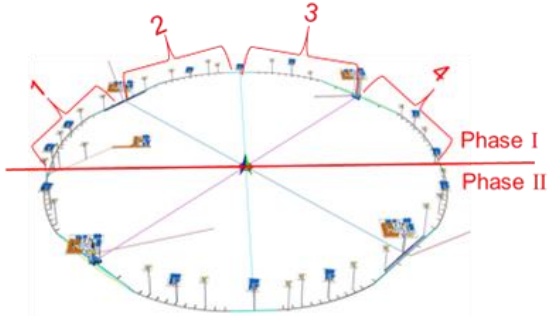
Error budget

Fiducializaton/mm	measurement/mm	adjustment /mm	Total/mm (relative error of adjacent components)
0.05	0.05	0.05	0.087

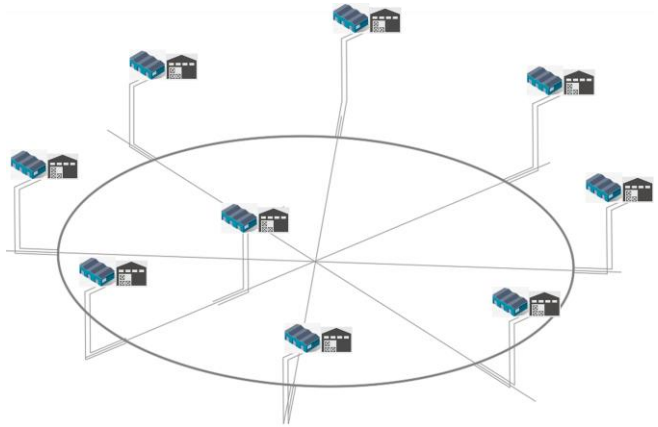
4、Component installation and alignment

- project period is :3 years and 9 months





Ring tunnel installation plan



Test hall

Warehouse

- A segments parallel strategy is adopted.

Phase	Group	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Ⅰ	16	Network construction																																													
	16	Network measurement																																													
	16	Support setting out																																													
	16	Support installation																																													
	32+32	Component installation																																													
Ⅱ	16	Network construction																																													
	16	Network measurement																																													
	16	Support setting out																																													
	16	Support installation																																													
	32+32	Component installation																																													
	64	Smooth alignment																																													

4、Component installation and alignment

- Alignment personnel plan

	Surface network measurement geoid refining	Tunnel control network construction	Tunnel control network measurement	Ring support setting out	Ring component alignment	Linac\TL\MDI\ Inspection measurement	Fiducialization & pre-alignment
Group×(number of people/group)	16 x （2）	16 x （2）	16 x （2）	16 x （2）	32 x （3）	4 x （3）	16 x （2）
Number of people	32	32	32	32	96	12	32
Working months	4	18	18	16	24	60	84
Months ×Number of people	128	576	576	512	2304	720	2688
Total Months ×Number of people	7504						

Summary

- For a hundred-kilometer long accelerator alignment, the irregular undulation of the geoid has to be considered and a geoid refinement scheme has been made.
- Based on the quasi-geoid model, a 3D control survey plan was developed, includes 3 levels control network, surface and tunnel connection measurement and observations processing.
- To improve installation efficiency, a segments parallel strategy is adopted, and the personnel requirements was estimated.

Thank You !