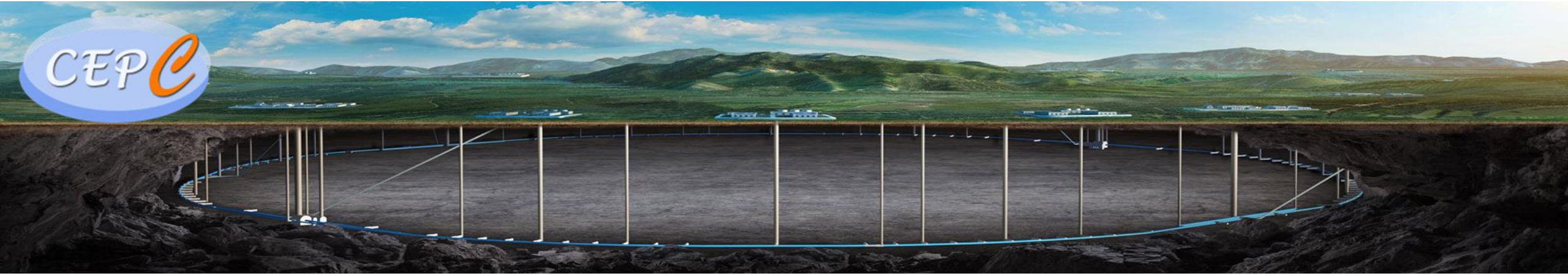


# CEPC alignment and Installation

**Wang xiaolong**

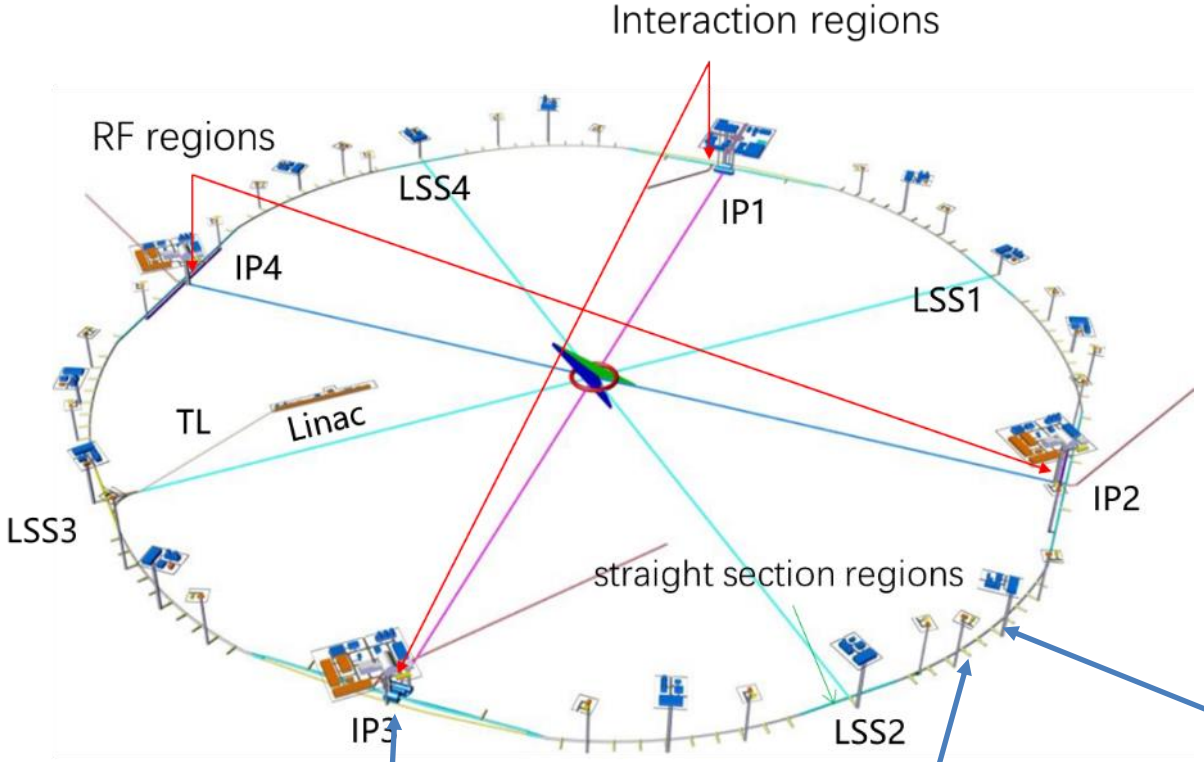
On behalf of CEPC Alignment and Installation Group

CEPC International Workshop
Oct. 23-27, 2023, Nanjing

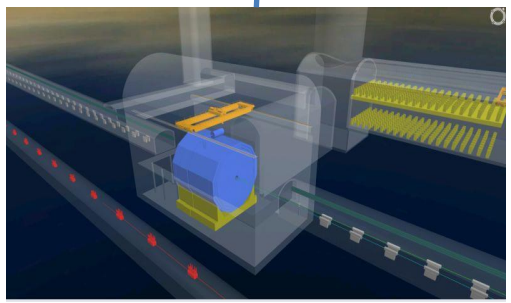
# Contents

# 一、Introduction

## Alignment scope

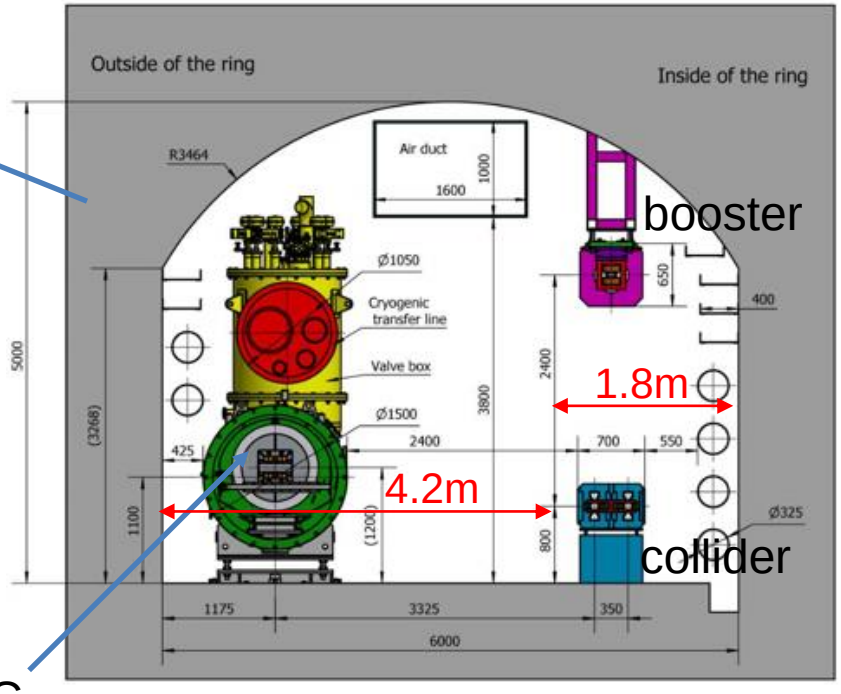



*Linac: **1.6km***
*TL:1.5km*
*Circumference of ring tunnel:100km*
*Collider: **100**km*
*Booster: 100km*
*Tunnel cross section: 6X5m*



**Interaction region**

**Ring tunnel**




SPPC

**Tunnel cross section**

# 一、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 |

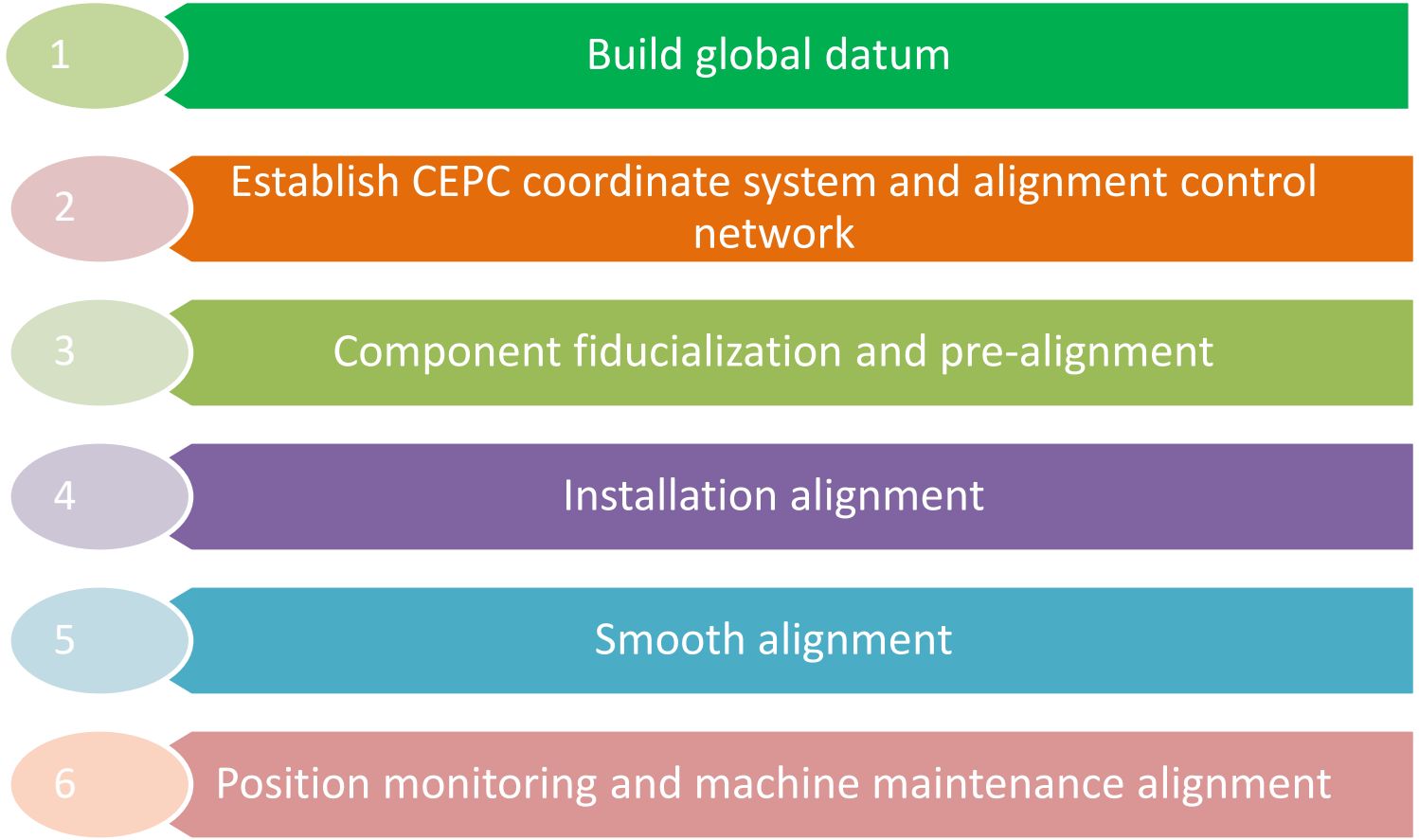
# 一、Introduction

- 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 | 0.05 | 0.05 | 0.1 | 0.1 | 0.1 | 0.1 |
| IR Solenoid | 0.2 | 0.2 | 0.3 | 0.5 | 0.5 | 0.5 |

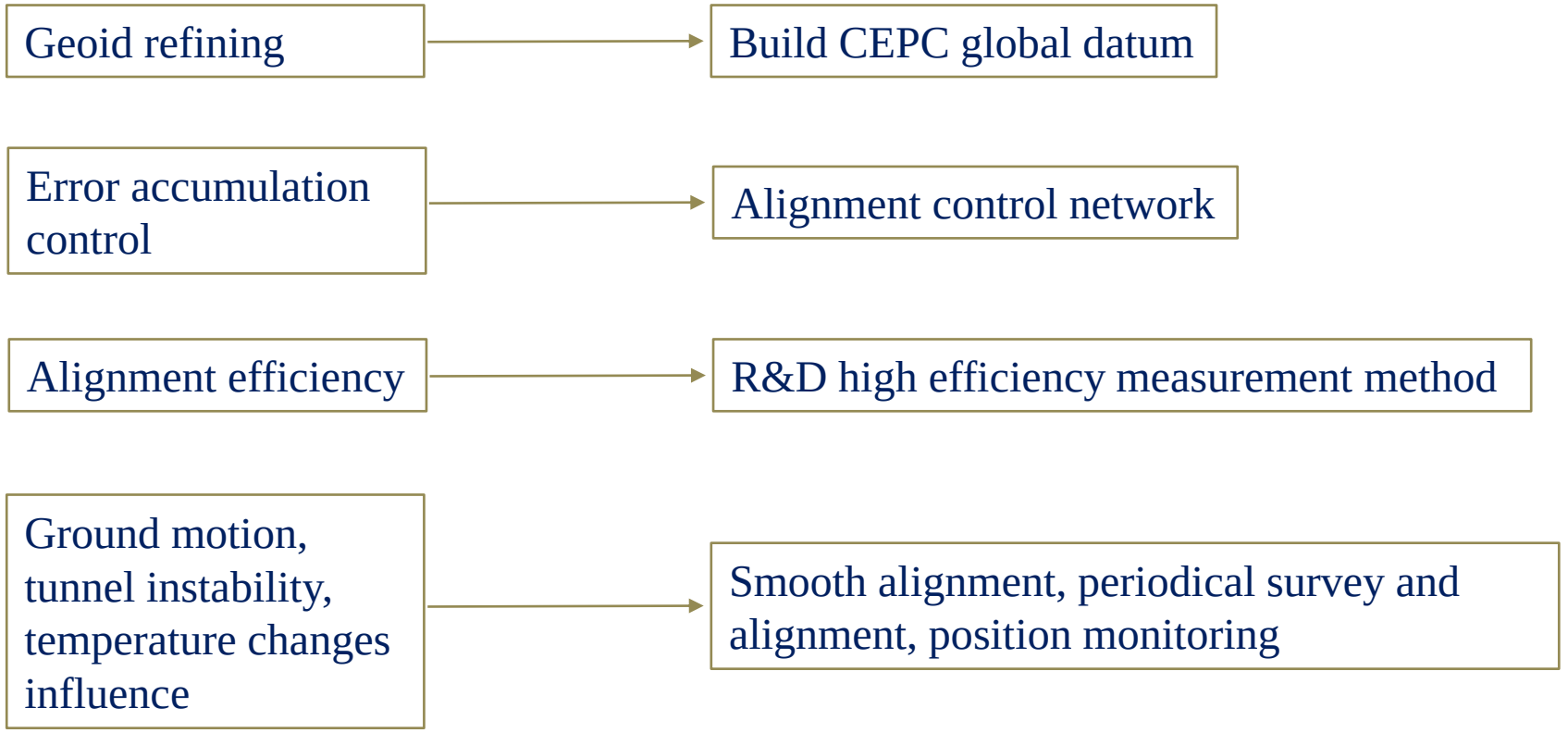
# 一、Introduction

- The goal of CEPC alignment : Adjusting all of the components to the designed positions within the specified tolerance and providing a smooth beam orbit under the absolute position control.
- Steps of alignment



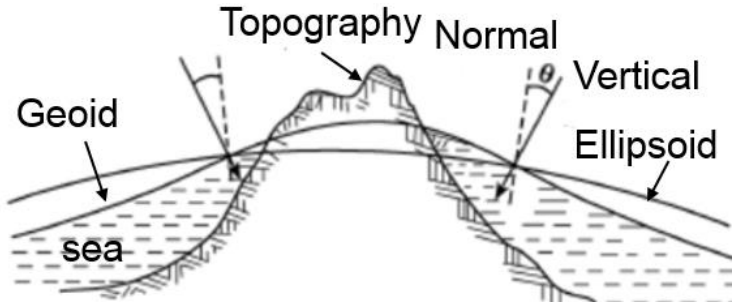
# 一、Introduction

- Key issues of CEPC alignment



# 2、CEPC global datum

CEPC scale is very large，performing the alignment it must take into account the Earth's gravity field influence.

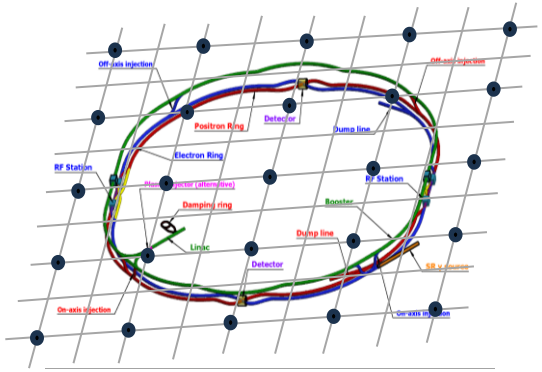



① Quasi-Geoid model: global datum for the height coordinate calculation.

② Vertical deflection model: global datum for the instrument coordinate system vertical axis orientation in the CEPC coordinate system.

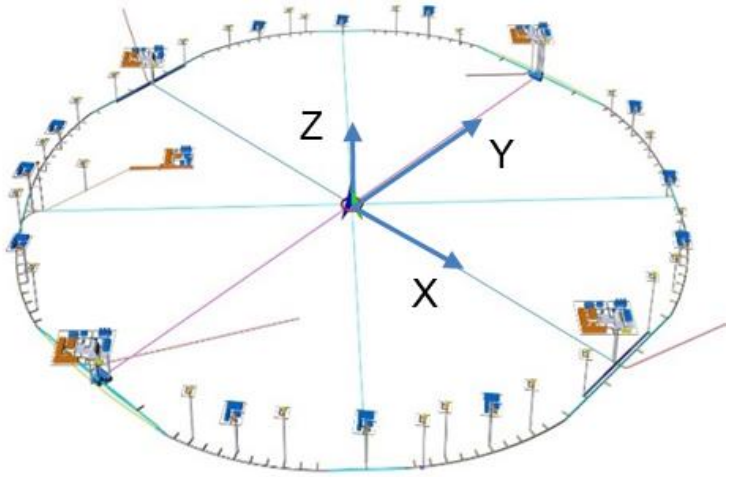
- Build method:
  - Establish a measurement network covering the CEPC area.
  - Carry out GNSS, level, gravity and vertical deflection measurement
  - Using latest technologies to build the models.
- goal：Quasi-Geoid model accuracy is better than10mm；vertical deflection model accuracy is better than 1.0″.

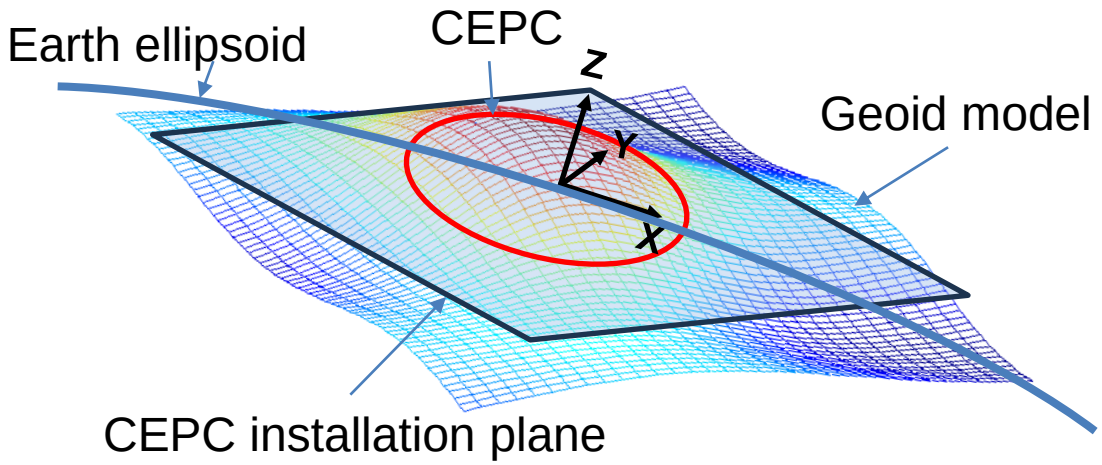
Measurement network



# 3、CEPC coordinate system

- CEPC coordinate system definition
  - Origin is in the ring center, XY plane is the machine installation plane.
  - In CGCS2000 coordinate system, we can design the coordinates of the origin , the points on x-axis and y-axis, make the XY plane best fit with the local geoid model.



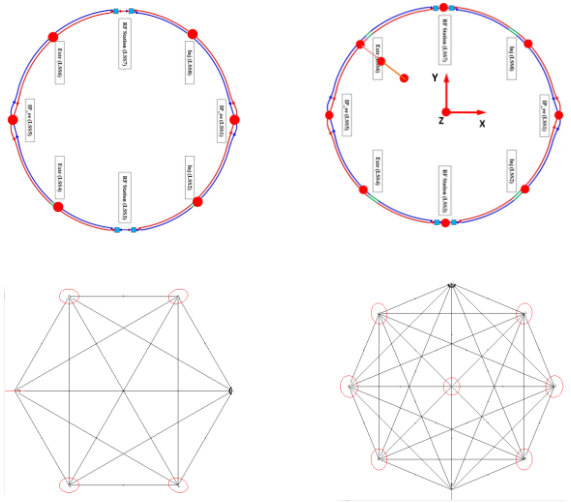
# 4、CEPC alignment control network

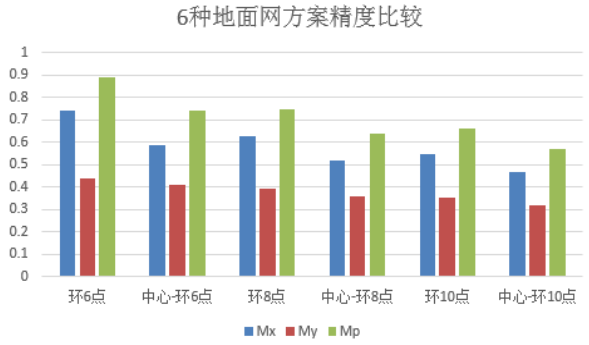
- Control network： provide an unified location reference frame for CEPC alignment and control the error accumulation；
- 3 levels control network
  - Surface control network
  - Backbone control network
  - Tunnel control network

# 4、CEPC alignment control network

## Surface control network

- CEPC global position control, high precision constraint points for tunnel control network.
- 6 layout schemes have been compared
  - Ring 6 points
  - Ring 6 points + 1 center point
  - Ring 8 points
  - Ring 8 points + 1 center point
  - Ring 10 points
  - Ring 10 points + 1 center point

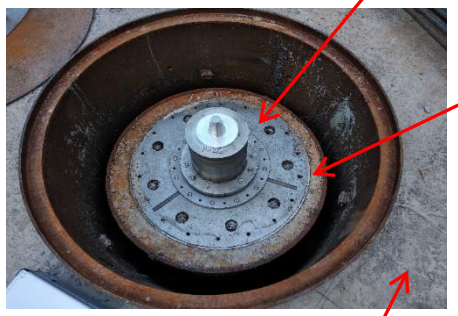


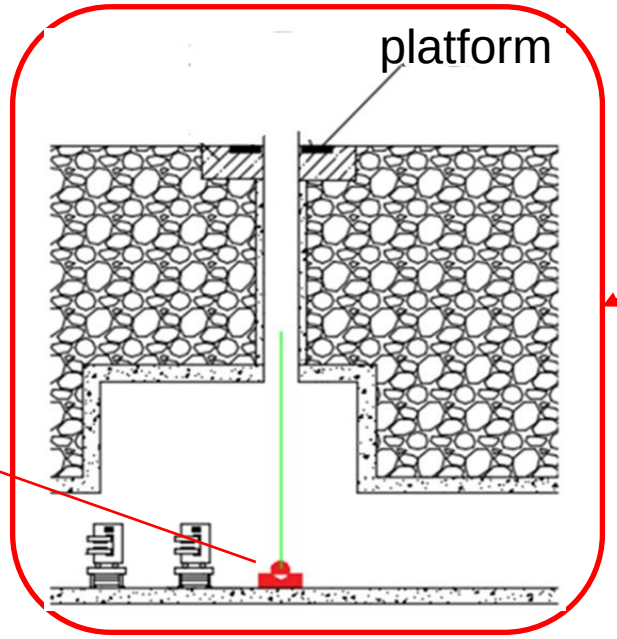


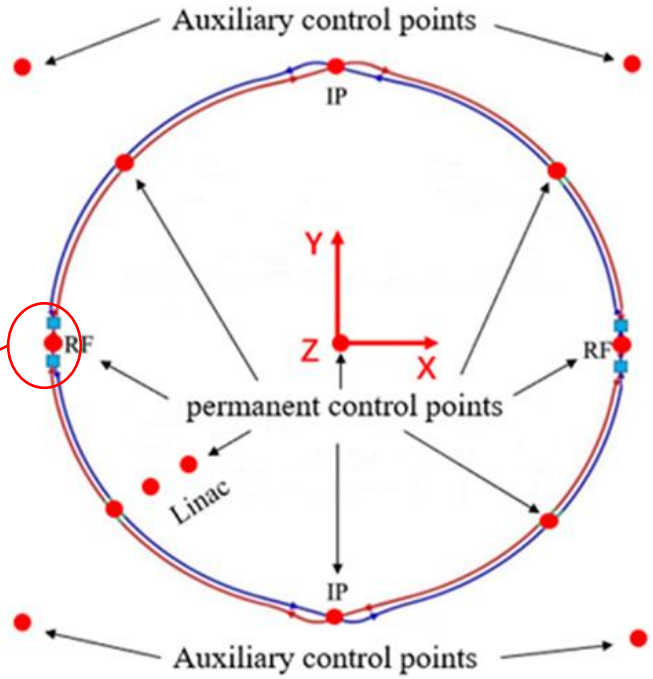

- Accuracy will be improved with the increasing of control points but the effect will wear off

# 4、CEPC alignment control network

- Considering the cost and the accuracy requirements, the ring 8 points + 1 center point scheme is plan to be adopted.
- Structure of the surface control network





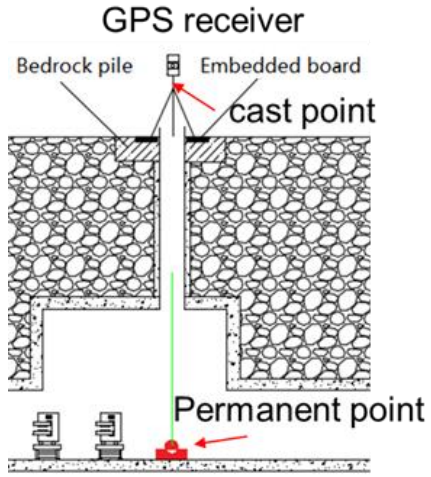



# 4、CEPC alignment control network

- Surface control network measurement:

Planar measurement → GNSS

Elevation measurement → Level

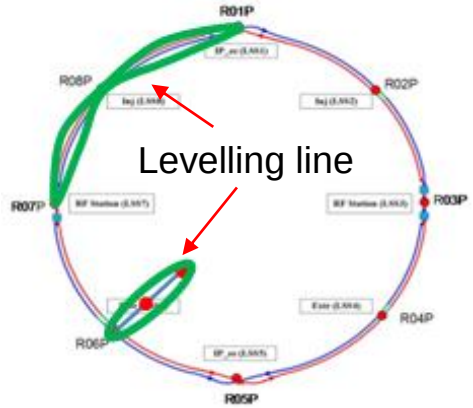


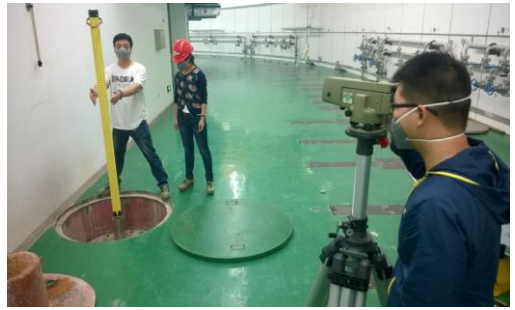


- Surface control network measurement accuracy： 7mm；

Personnel and time requirements

| | Planar measurement | Elevation measurement |
|---|---|---|
| **Group** | 16 | 4 |
| **Week** | 3 | 4 |

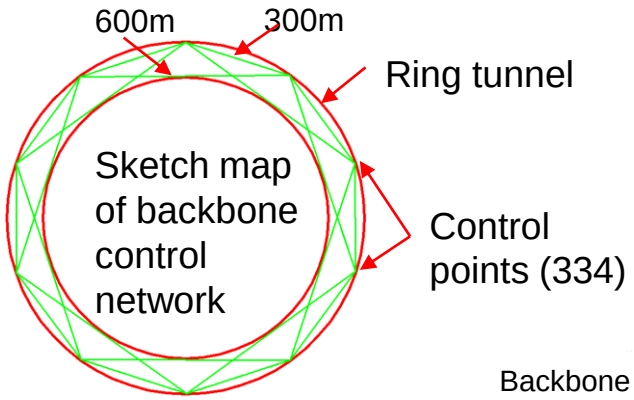


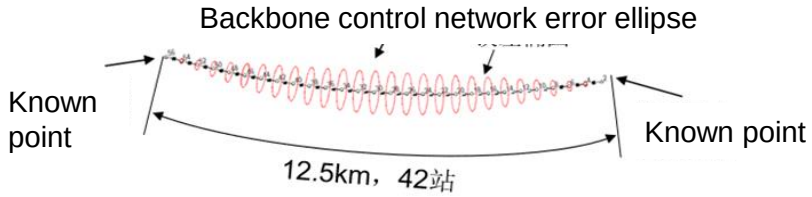
# 4、CEPC alignment control network

## Backbone control network

- Strengthen the tunnel control network，reduce error accumulation.
- Built on the ring tunnel floor.




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



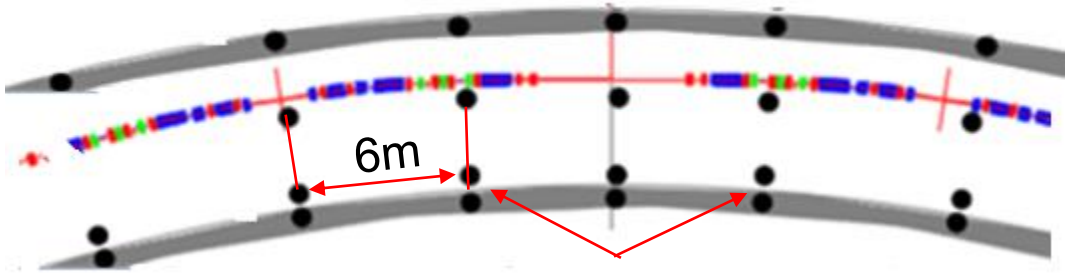

| Planar measurement | |
|---|---|
| **Instrument** | Total station、gyro-theodolite |
| **Group** | 8 |
| **Working day** | 11 (4points/group/day) |
| **Accuracy** | Standard point position error is 3.85mm. Relative point position error is 0.79mm（300m） |

| Elevation measurement | |
|---|---|
| **Instrument** | Level |
| **Group** | 8 |
| **Working day** | 4（4km/group/day） |
| **Accuracy** | Maximum point position error is 7mm, Relative point position error is 0.5mm（300m） |

# 4、CEPC alignment control network

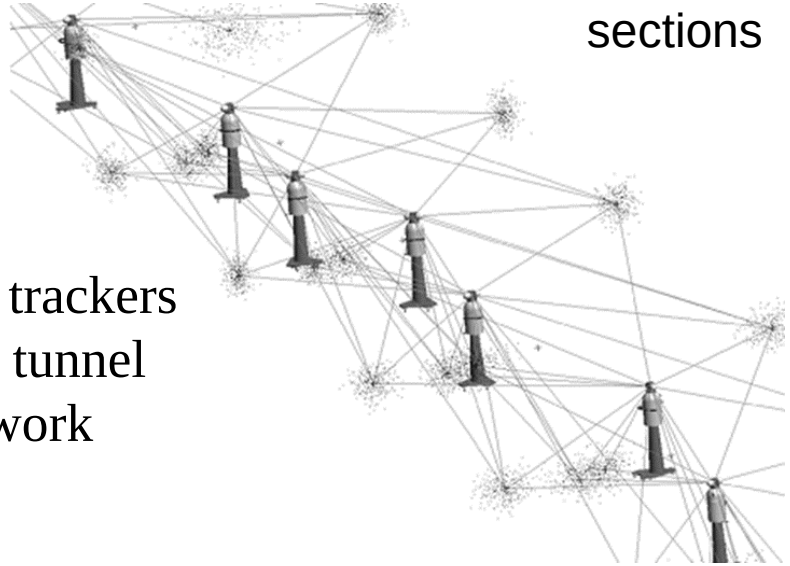
## Tunnel control network

- Providing position reference for component installation and alignment

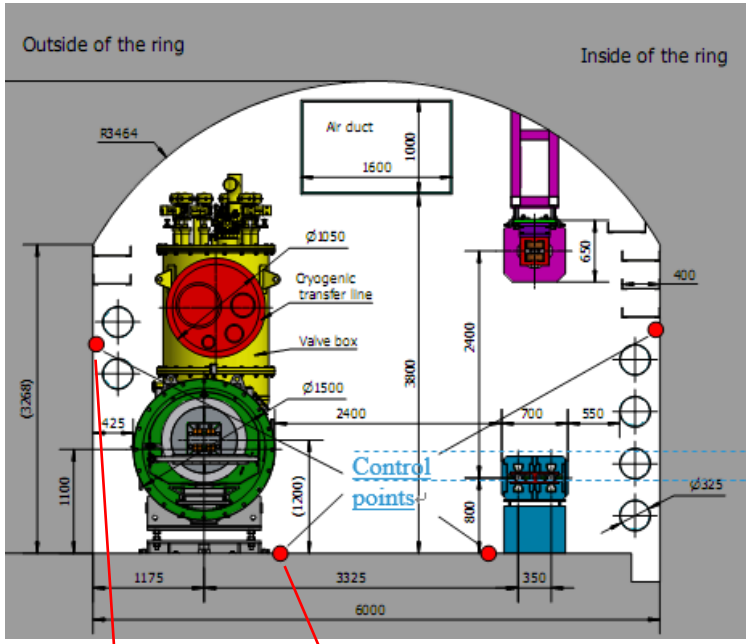


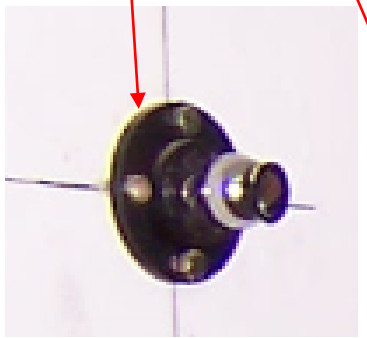

Control points

More than 18800 sections



- Using laser trackers to carry out tunnel control network survey



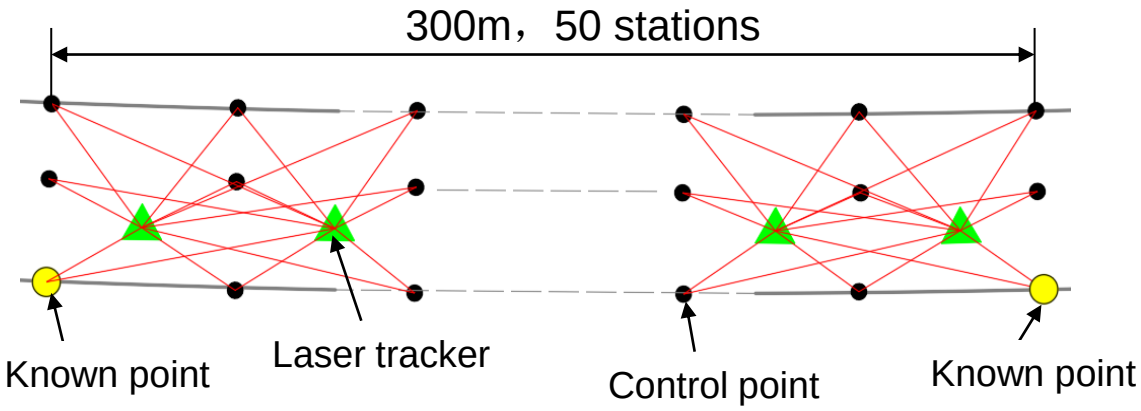



Wall control point

Ground control point

# 4、CEPC alignment control network

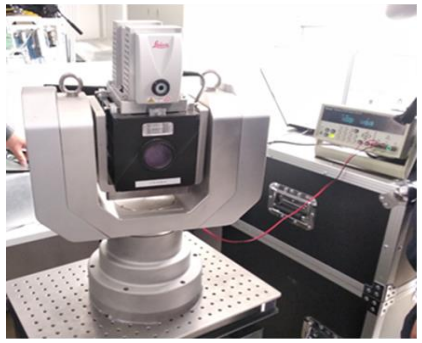
- Simulation
- According to angular accuracy 2″, distance accuracy 0.015mm+2ppm to generate the simulated observations.
- The standard point position error is 0.38mm and the relative point position error within 6m is better than 0.074mm.




| Time estimation for laser tracker measurement | | | | |
|---|---|---|---|---|
| **Instrument** | **Work load** | **Speed (1group/1day)** | **Group** | **Month** |
| Laser tracker | 18884 stations | 8 stations | 16 | 6 |

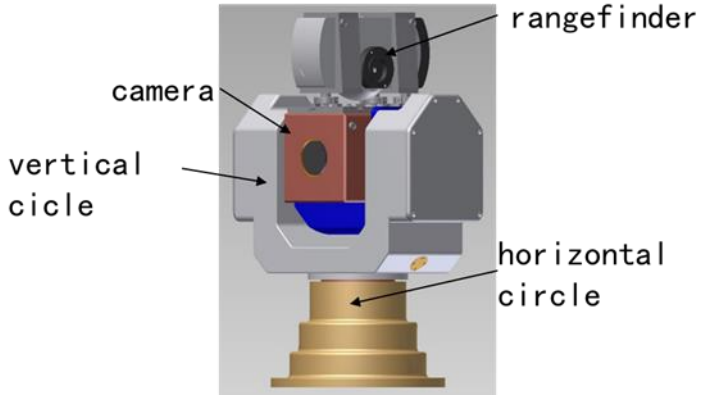
# 4、CEPC alignment control network

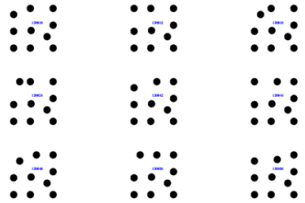
- Visual instrument
- A new kind measurement instrument: photogrammetry, distance, angle measurement functions ,
- Advantage : can observe multiple points in a single measurement
- Objective: high accuracy, high efficiency measurement
- Two generations prototypes have been developed.



Ⅰ

Ⅱ



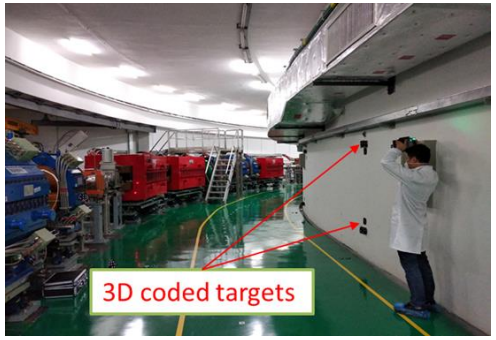



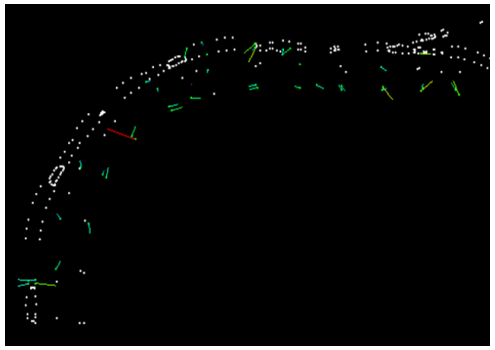
million-capacity coded target

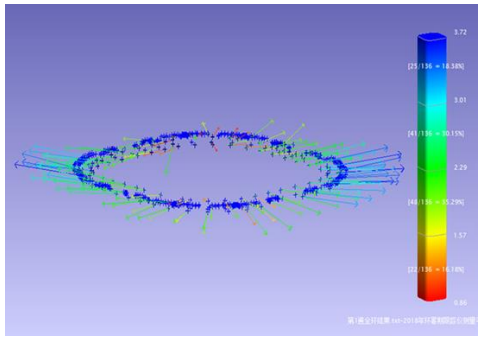
five-face target

# 4、CEPC alignment control network

- Carried out 2 times photogrammetric experiments in CSNS RCS ring.



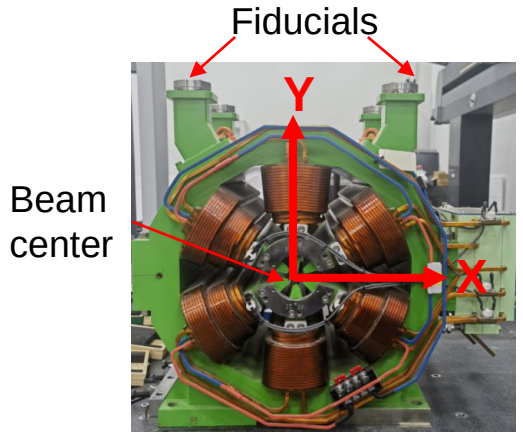


- Efficiency can be increased by 3 times.
- Accuracy need to be improved.
- Currently, visual instrument calibration is under studying. After that, measurement experiment will be performed to verify its accuracy.

| Time estimation for Visual instrument measurement | | | | |
|---|---|---|---|---|
| **Instrument** | **Work load** | **Speed (1group/1day)** | **Group** | **Month** |
| Visual instrument | 18884 stations | 24 stations | 12 | 2.6 |

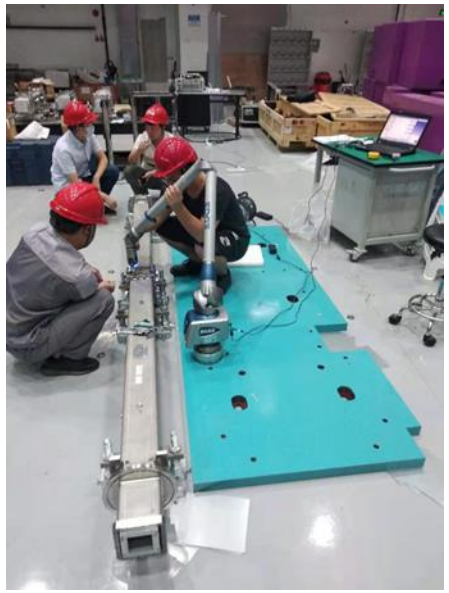
# 5、Fiducialization & pre-alignment

- Purpose of fiducialization： to relate the nominal beam center of a component to its fiducials, then, according to the designed beam position, we can calculate the nominal coordinates of the fiducials in CEPC coordinate system.
- Geometric measurement, by using laser tracker, measuring arm, optical instrument.

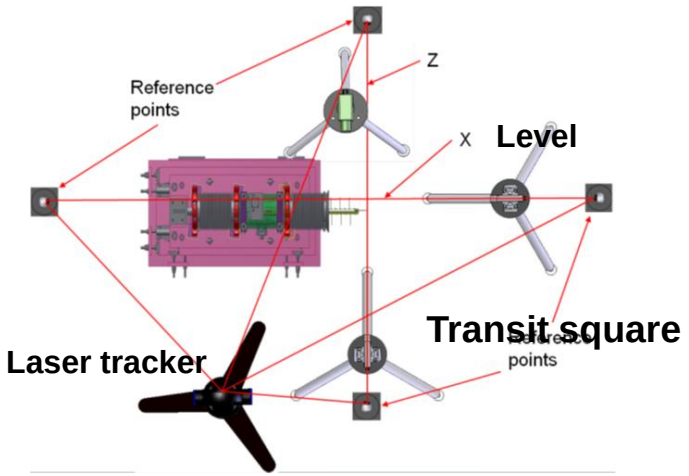



| Transversal /mm | Vertical /mm | Longitudinal /mm |
|---|---|---|
| 0.05 | 0.05 | 0.08-0.15 |

laser tracker

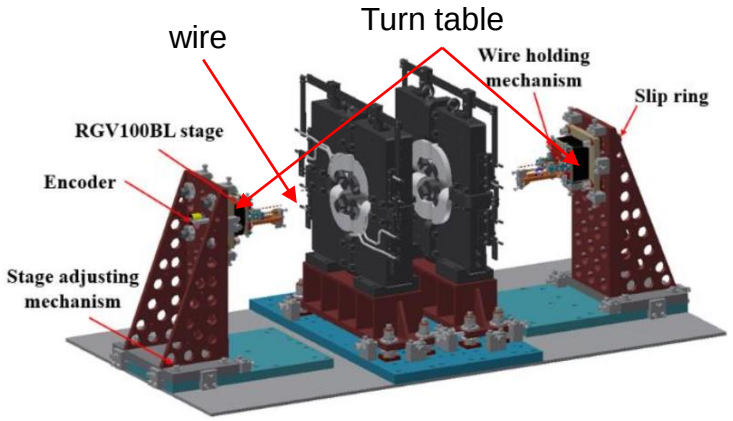


measuring arm



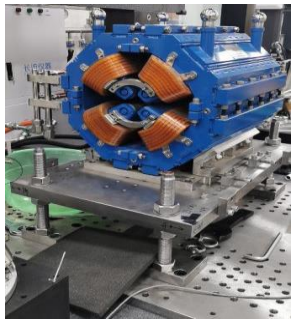
# 5、Fiducialization & pre-alignment

- Quadrupoles and sextupoles fiducialization will based on their magnetic center.
- A rotating wire magnet fiducialization system has been developed and successfully used for HEPS quadrupole and sextupole fiducialization.




Rotating wire measurement system

- Technical features
  - The rotating wire measurement system enables high precision magnetic center measurement.
  - 6-DOF stages allows for efficient and automatic adjustment of the wire.
  - Using an image probe for the wire position accurate measurement.
  - The CMM can realize magnet surface high precision automatic measurement.



Support and adjustment mechanism

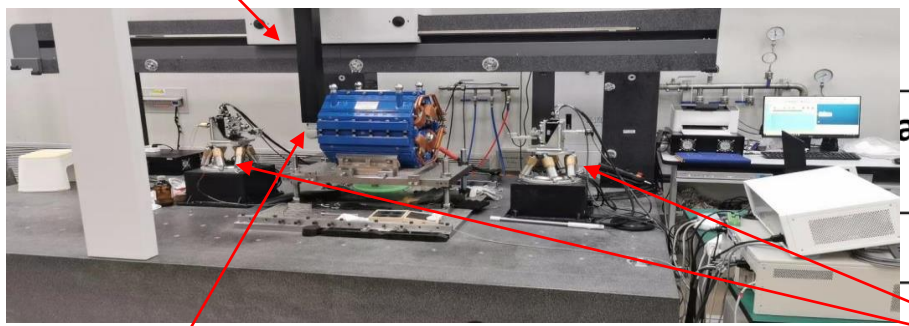
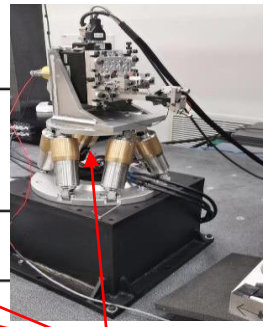



Image probe



6 DOF stage

| Transversal /mm | Vertical /mm | Longitudinal /mm |
|---|---|---|
| 0.014 | 0.014 | 0.05 |

# 5、Fiducialization & pre-alignment

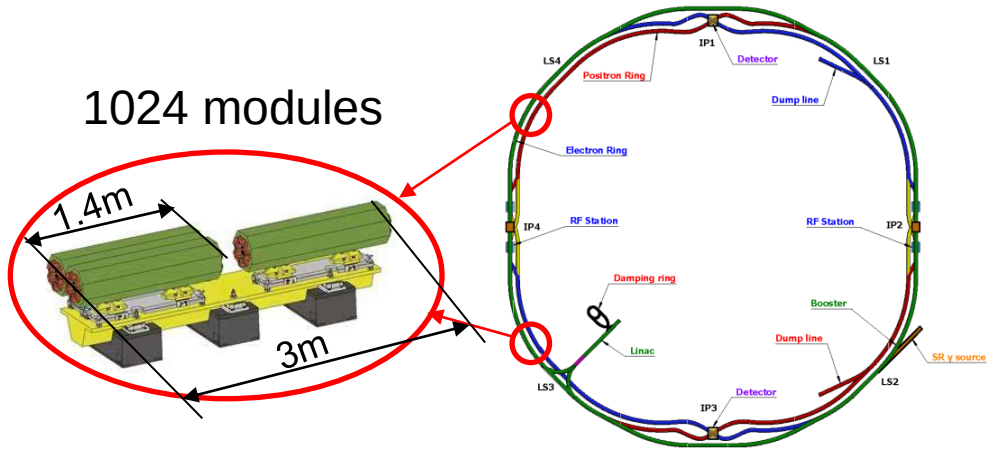
| Group number and time estimation of component fiducialization | | | | | |
|---|---|---|---|---|---|
| Component | Instrument | Number | Speed（1group/day） | Group | Month |
| Dipole | Laser tracker & Optical instrument | 31259 | 2 | 16 | 39.1 |
| Quadrupole | Rotating wire | 8320 | 3 | 8 | 14 |
| Sextupole | Rotating wire | 3348 | 3 | 8 | 5.58 |
| Corrector | Measuring arm | 9799 | 4 | 16 | 6.12 |
| BPM、PR、DCCT、kicker | Measuring arm | 6132 | 4 | 16 | 3.83 |
| Septum Magnet | Laser tracker | 102 | 1 | 16 | 0.26 |
| Kicker | Laser tracker | 18 | 1 | 16 | 0.05 |
| Electrostatic separator | Laser tracker | 32 | 2 | 16 | 0.04 |
| Collimator /dump | Laser tracker /Optical instrument | 44 | 2 | 16 | 0.06 |
| Solenoid | Measuring arm | 37 | 4 | 16 | 0.02 |
| Accelerating structure | Laser tracker | 577 | 2 | 16 | 0.72 |
| Cavity | Measuring arm | 4 | 2 | 16 | 0.01 |
| Total | | | | 16 | 70 /（5.9 years） |

# 5、 Fiducialization & pre-alignment

- Sextupoles installation of collider ring will apply the pre-alignment method.
- Advantages： Can get higher relative position accuracy of the components on one girder and can save tunnel installation time.

Pre-alignment error budget

| Error item | Error/mm | Measurement instrument |
|---|---|---|
| Magnet fiducialization | 0.014 | Rotating wire |
| Measurement | 0.02 | Laser tracker |
| Adjust & lock | 0.03 | |
| Magnet open and close | 0.01 | |
| transport | 0.02 | |
| **Total** | 0.045 | |

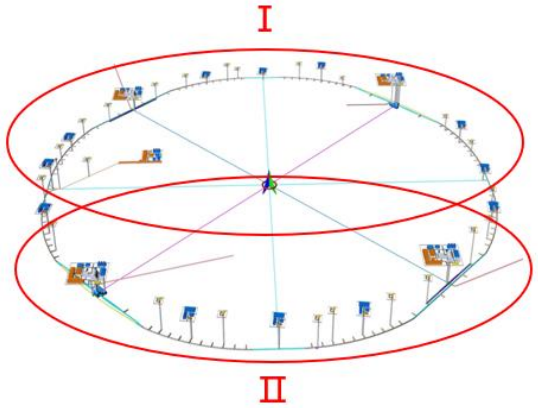



Time estimation of pre-alignment

| Module number | Speed（1group/day） | Group | Month |
|---|---|---|---|
| 1024 | 0.5 | 16 | 5.2 |

# 6、Tunnel installation alignment

- Installation scheme is made based on the civil construction schedule, includes two phases.
- project period is :3 years and 9 months




- Tasks:

1. Control network construction.
2. Control network measurement
3. Support setting out and installation
4. Component installation and alignment.
5. Smooth alignment

Ring tunnel installation plan

| 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 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

# 6、Tunnel installation alignment

| Collider ring alignment manpower and time estimation | | | | |
|---|---|---|---|---|
| Component | Number | Piece（1 group / day) | Group | Month（25 workdays / month） |
| Dipole | 3170 (16258 cores) | 3 | 16 | 13.5 |
| Quadrupole | 4148 | 4 | 16 | 2.6 |
| Sextupole | 3176 | 4 | 16 | 2.0 |
| Corrector | 7088 | 6 | 16 | 3.0 |
| BPM\PR\DCCT | 3544 | 6 | 16 | 1.5 |
| Septum Magnet | 68 | 3 | 16 | 1.5 |
| Kicker | 8 | 4 | | |
| Cryomodule | 32 | | | |
| Electrostatic separator | 32 | 2 | | |
| Superconducting Magnets | 4 | | | |
| Collimator\ dump | 36 | 4 | | |
| Total | | | 16 | 24 |

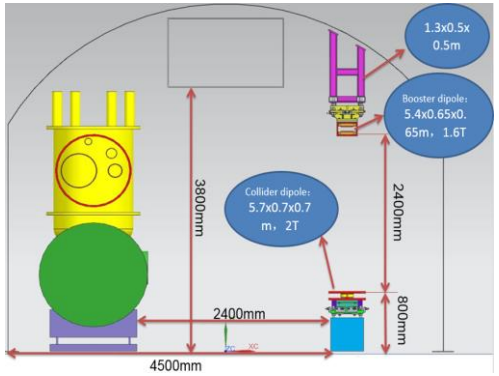
| Booster alignment manpower and time estimation | | | | |
|---|---|---|---|---|
| Component | Number | Piece（1 group / day) | Group | Month（25 workdays / month） |
| Dipole | 14844 | 2 | 16 | 18.5 |
| Quadrupole | 3458 | 4 | 16 | 2 |
| Sextupole | 100 | 4 | 16 | 0.1 |
| Corrector | 2436 | 6 | 16 | 1 |
| BPM\PR\DCCT | 2408 | 6 | 16 | 1 |
| Cryomodule | 12 | | 16 | 1.4 |
| Septum Magnet | 32 | 2 | | |
| Kicker | 8 | 4 | | |
| Total | | | 16 | 24 |

# 6、Tunnel installation alignment

| Linac DR TL installation and alignment time estimation | | | | |
|---|---|---|---|---|
| Component | Number | Piece (1 group / day) | Group | Month（25 workdays / month） |
| Dipole | 135 | 3 | 1 | 1.8 |
| Quadrupole | 714 | 4 | 1 | 7 |
| Sextupole | 72 | 4 | 1 | 1 |
| Corrector | 275 | 6 | 1 | 1.8 |
| BPM\PR\DCCT | 180 | 6 | 1 | 1.2 |
| Accelerating structure | 577 | 4 | 1 | 5.8 |
| Solenoid | 37 | 3 | 1 | 0.5 |
| SHB BUN<br>RF Cavity | 4 | 2 | 1 | 0.4 |
| Collimator dump | 8 | 3 | 1 | |
| Electron Source | 1 | | 1 | |
| Positron Source | 1 | | | |
| Septum Magnet | 2 | | | |
| Kicker | 2 | | | |
| Total | | | 1 | 19.5 |

# 6、Tunnel installation alignment

- Using the tunnel control network as reference and laser trackers as measurement instruments to perform components installation alignment.



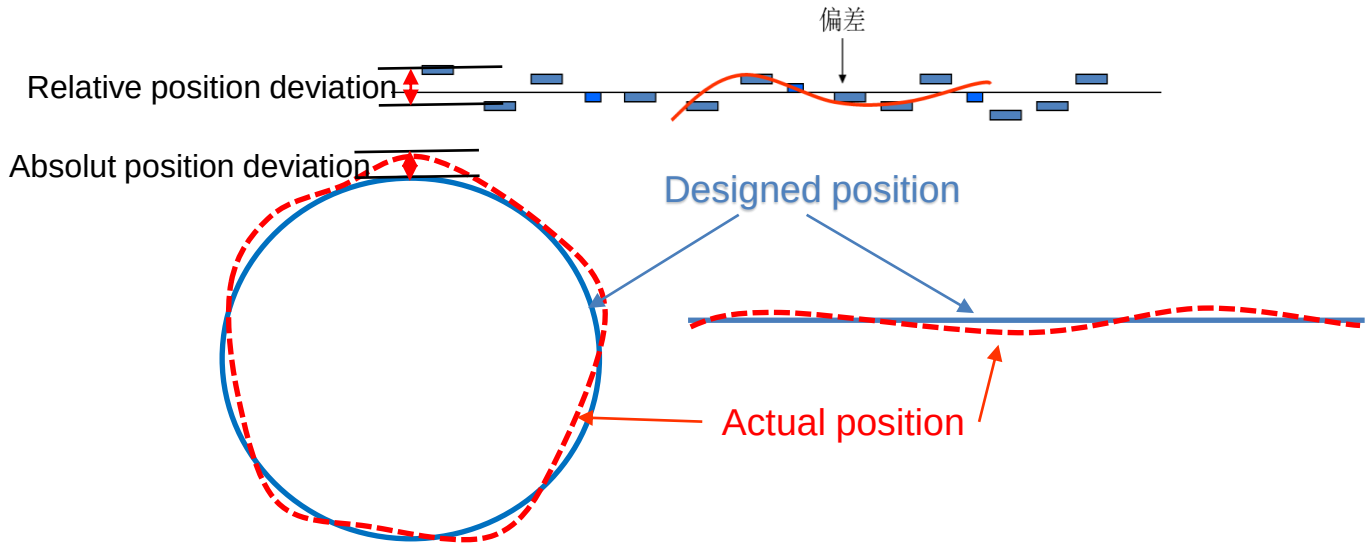

- Various vehicles and hoisting machineries will be needed.

- Smooth alignment
  - Although during the initial installation all of the components are adjusted within the required tolerance, due to ground motion, temperature change and other factors, the control network and machine occur deformation will be inevitable. So, after the initial installation and alignment, it needs to carry out an overall survey to check the deformations, and repeat the alignment work to reduce deformation.
  - Considering the enormous workload of align all of the components to their designed position, we will adopt a smooth alignment strategy instead.

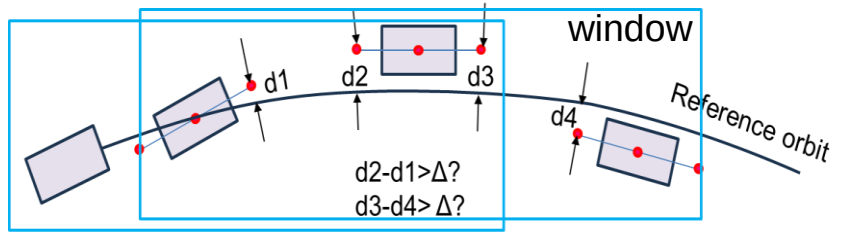
# 6、Tunnel installation alignment

- Smooth alignment will focus on the relative position alignment between adjacent components and relax the absolute position accuracy requirement. The goal is to provide a smooth orbit for beam operation.

- Calculation method: Using a window covers three adjacent components. Examining the offsets between the middle and both sides components, if any offset beyond 0.08mm, then calculate new position of the middle component. This is an iterative process, each time the window moves forward one component and repeat the calculation. It will lasted until there is no component overshoot.



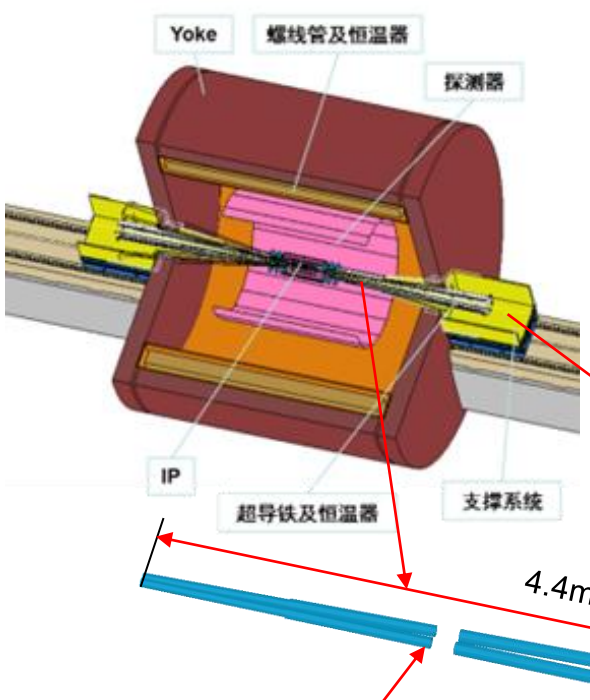

- According to the smooth calculation result adjust the components, and this smooth alignment will be repeated 2-3 times.



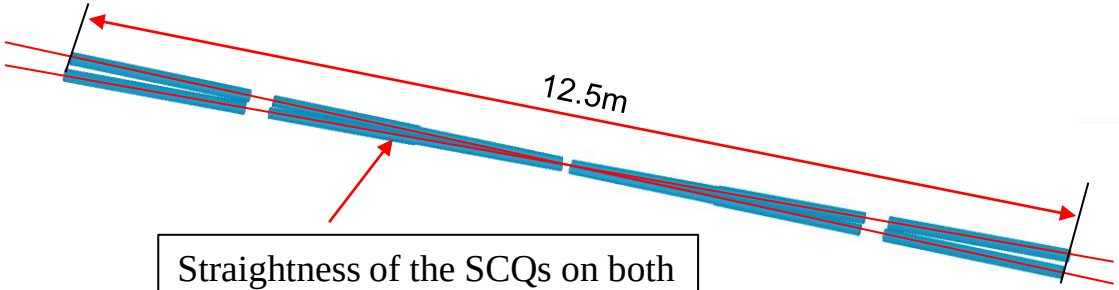

Quadrupole / Sextupole alignment accuracy estimation (1σ)

| Fiducializaton/mm | measurement/mm | adjustment /mm | Total/mm |
|---|---|---|---|
| 0.014 | 0.05 | 0.08 | 0.1 |

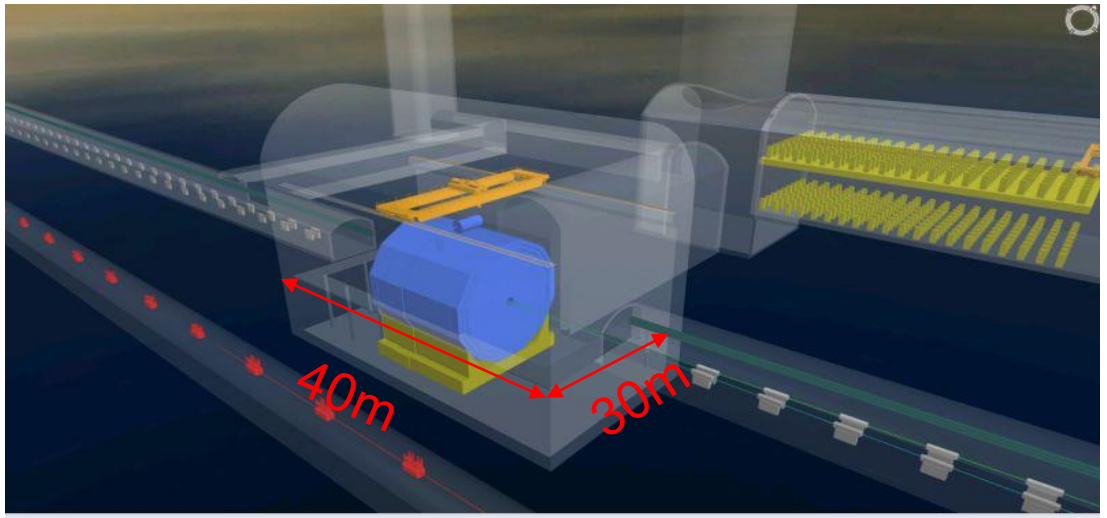
# MDI alignment

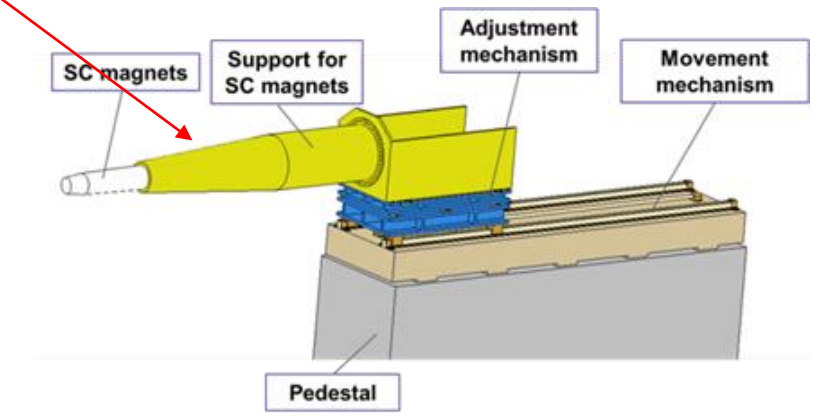



Relative position accuracy of the SCQ ≤±50μm



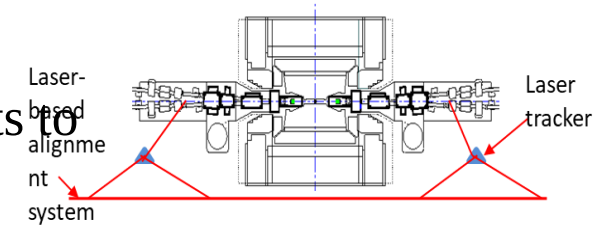

Straightness of the SCQs on both sides ≤±100μm

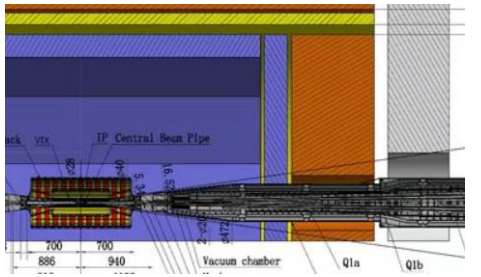


# MDI alignment

- MDI alignment is still under studying, here can only propose a preliminary strategy.
- Alignment strategy
  - Install SCQs and solenoids into the cryostat and performing a pre-alignment
  - Establish a laser alignment system beside the detector and adjusting the laser beam parallel to the designed detector center line.
  - Using this laser alignment system as a reference, adjust the rails and cryostats to the designed position in vertical and transversal.
  - Push the cryostats into the detector along the rail.
  - The alignment error of the SCQs can be examined by using a vibrating wire.
- As the end of the cryostat is inserted into the detector, its position cannot be measured by a laser tracker, so it need to research cryostat position measurement method.
- The cryostat is designed as a cantilever structure, it is necessary to research the deformation monitoring method.



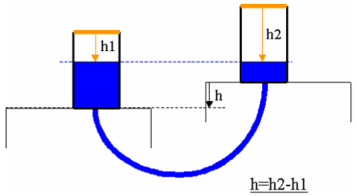



# 7、Deformation and solutions

- For CEPC such large-sized machine, it occurs deformation will be inevitable.
  - To find where occur the deformation, during the annual shutdown period, an overall measurement will be conducted.
  - Installation monitor system is an effective way to find deformations immediately.

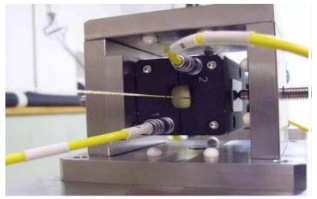
Settlement monitor

Hydrostatic Levelling System (HLS)

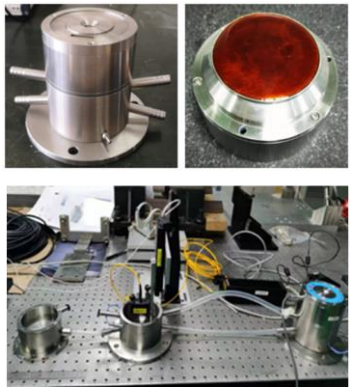



Component transversal and vertical monitor

WPS



  - Capacitive hydrostatic level sensor developed for HEPS



- Due to cost constraints, the monitoring sensors will not be installed evenly throughout the entire ring. We plan to install them in the interaction regions which have higher alignment accuracy requirement.

# Summary

- Considering the Earth gravity field influence to the measurement, two kinds of global datums need to be built.
- To control the error accumulation of large range measurement, a three levels control network has been designed
- In order to increase measurement efficiency, a new kind measurement instrument - visual instrument is under R&D.
- MDI alignment techniques need to be further studied.
- To cope with the deformation,  a smooth alignment strategy will be applied, annual survey will be conducted and monitoring systems will be installed.

Thank You !