



# CEPC Alignment and Installation Studies in EDR

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On behalf of CEPC Alignment and Installation Group

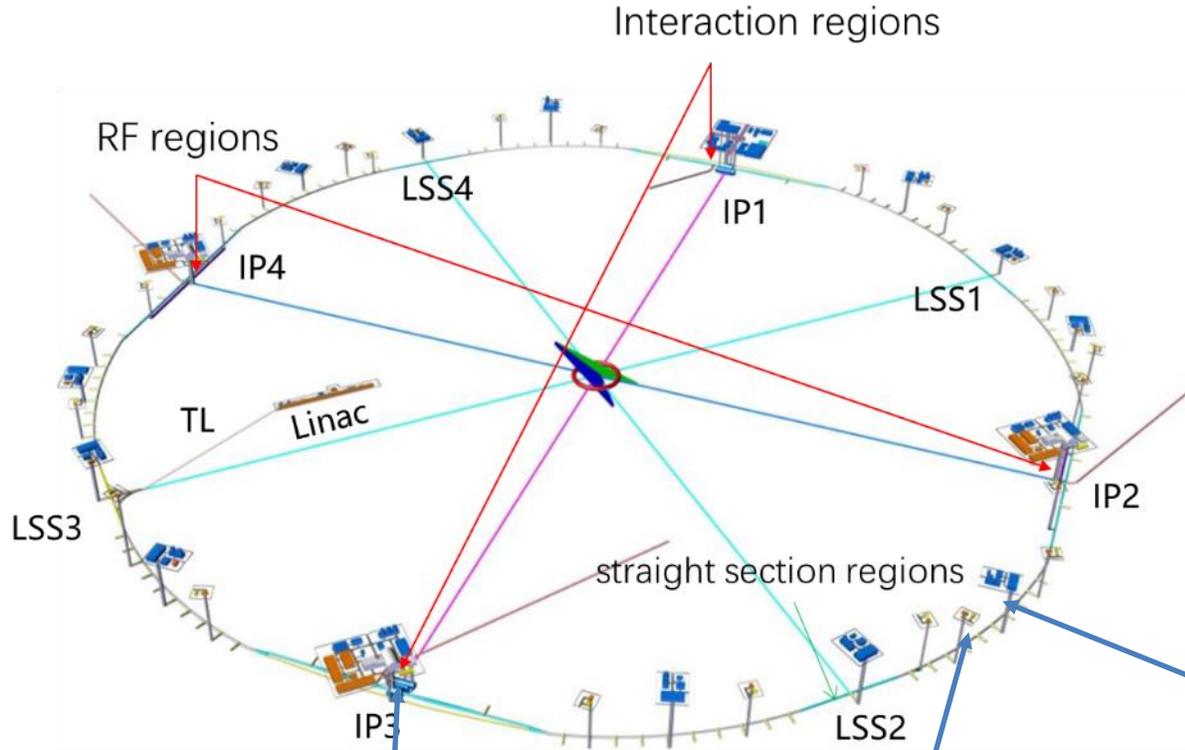
HKUST IAS Program on Fundamental Physics  
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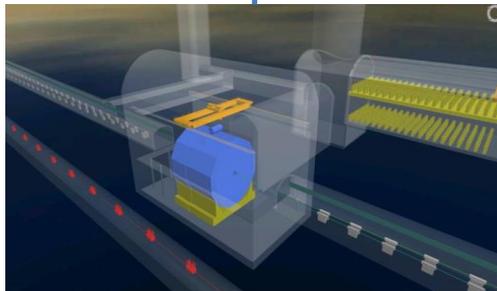
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- 1. Introduction**
- 2. Alignment and installation study progress**
- 3. summary**

# 1、 Introduction work scope



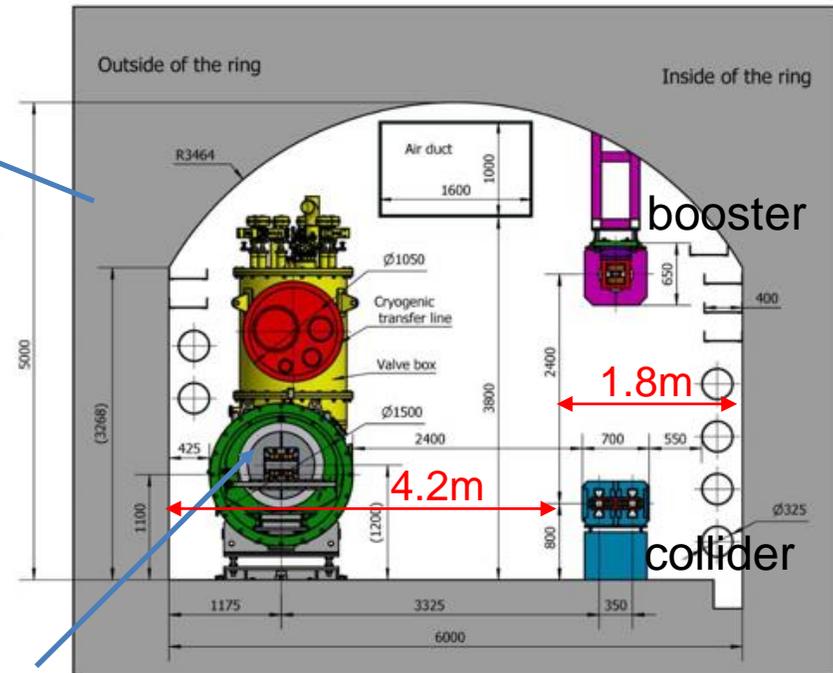
*Linac: 1.6km*  
*TL: 1.5km*  
*Circumference of ring tunnel: 100km*  
*Collider: 100km*  
*Booster: 100km*  
*Tunnel cross section: 6X5m*



**Interaction region**



**Ring tunnel**



**Tunnel cross section**

# 1、 Introduction

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- Quantity of components

Component	Collider Ring	Booster	Linac, DR, TL	Total
Dipole	13250 (core)	14866	135	28251
Quadrupole	4148	3458	714	8320
Sextupole	3176	100	72	3348
Corrector	7088	1200	275	8563
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
<b>Total</b>	<b>34396</b>	<b>23320</b>	<b>2008</b>	<b>56716</b>

# 1、 Introduction

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- Alignment accuracy requirement

Relative position accuracy requirement of adjacent components ( $1\sigma$ )						
Component	Transversal/mm	Vertical/mm	Longitudinal/mm	Roll/mrad	Pitch/mrad	Yaw/mrad
Dipole	0.1	0.1	0.2	0.1	0.2	0.2
Quadrupole	0.1	0.1	0.2	0.1	0.2	0.2
Sextupole	0.1	0.1	0.2	0.1	0.2	0.2
Corrector	0.3	0.3	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

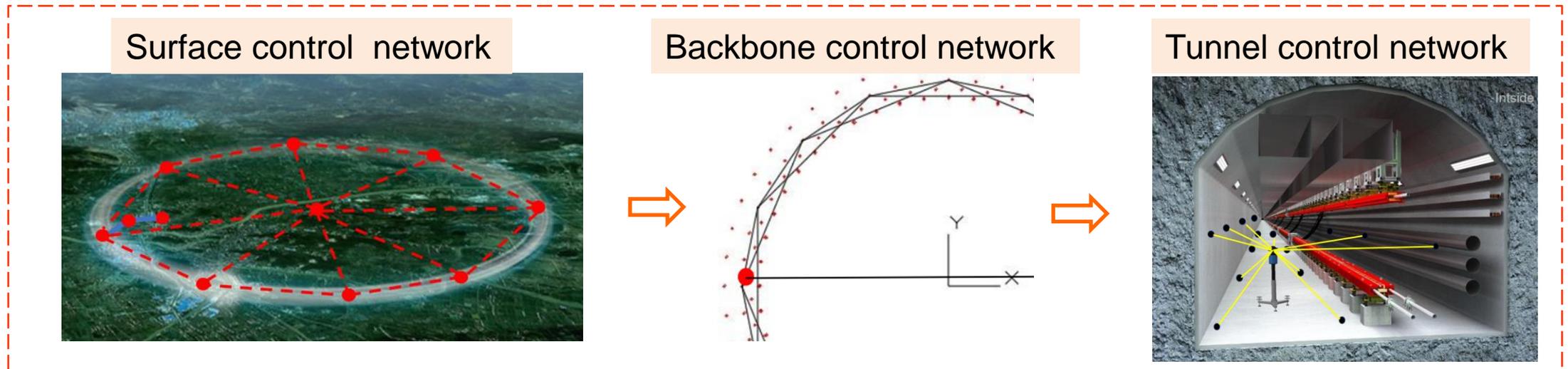
# 1、 Introduction

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- Key issues of CEPC alignment and installation
  1. For large scale measurement, it must consider the irregular undulation of the geoid and needs to carry out geoid refinement.
  2. To provide a positional reference frame for component alignment, it needs establish an accurate control network and control the error accumulation.
  3. To improve alignment and installation efficiency, it is necessary to R&D high efficiency measurement method, and optimize the installation plan.
  4. Challenge of MDI high accuracy alignment .

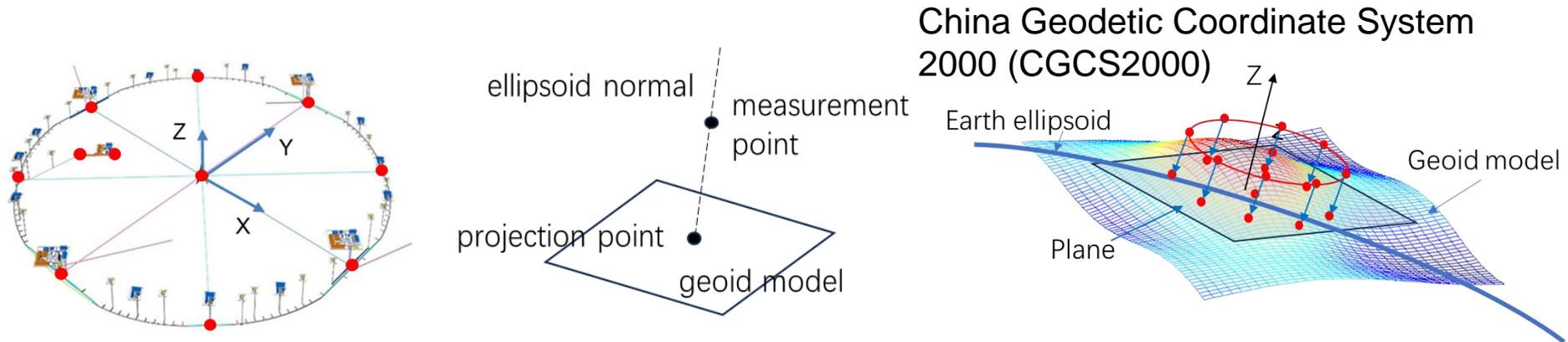
# 1、 Introduction

- CEPC alignment technical route
  - Build a high-precision quasi-geoid model as a global datum for the observations reduction;
  - Establish a three-levels control network to provide a positional reference framework for component installation and control error accumulation;

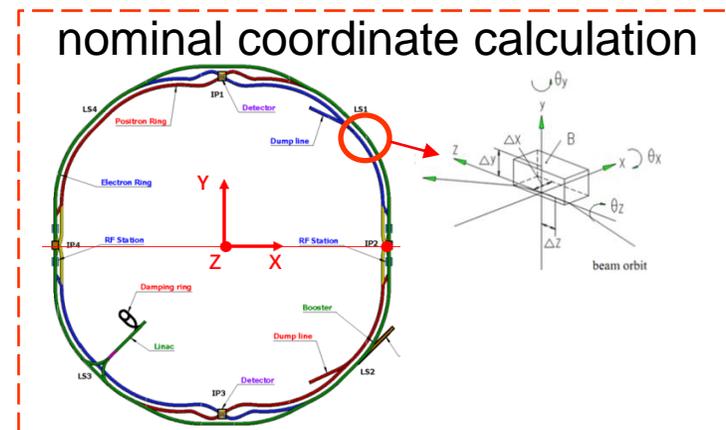
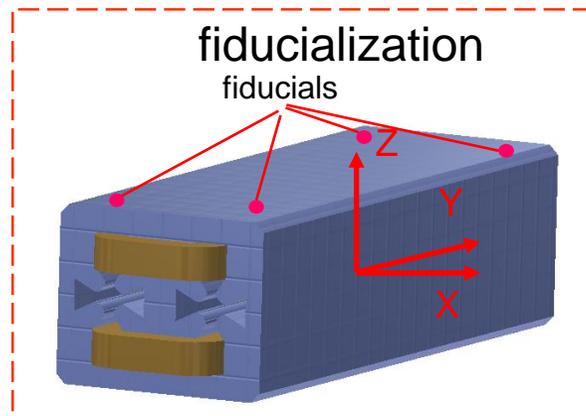


# 1、Introduction

- Use the surface network as a reference to establish CEPC coordinate system;



- Through fiducialization and coordinate transformation to calculate the nominal coordinates of the component fiducials in CEPC coordinate system;



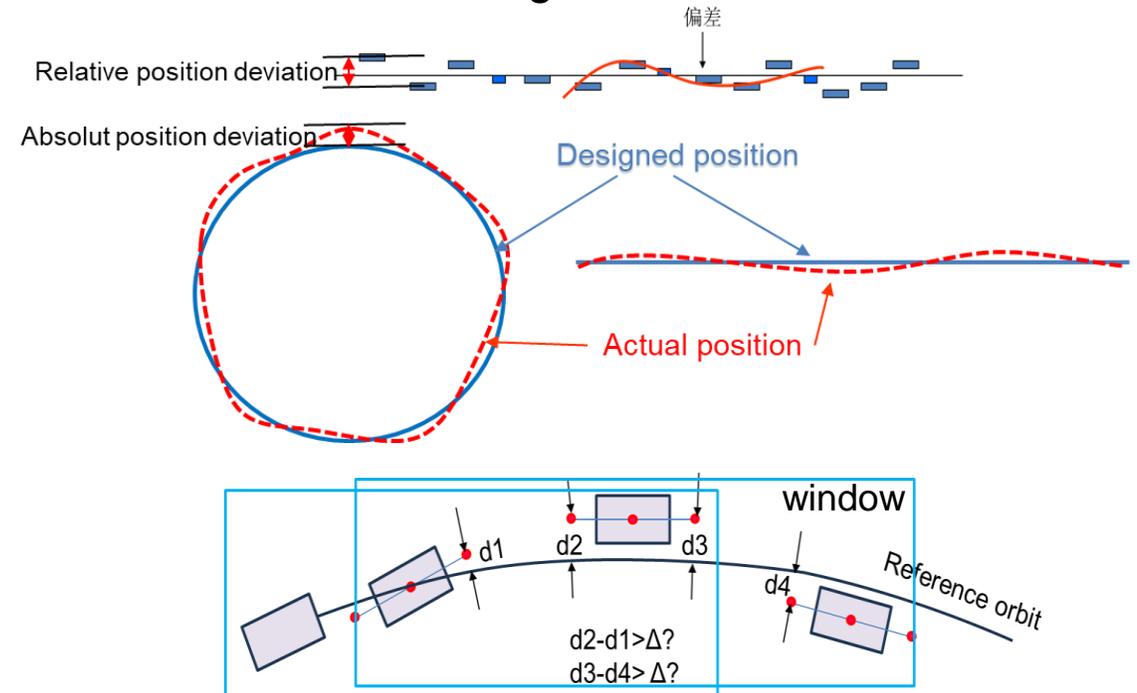
# 1、 Introduction

- Use the control network as a positional reference, by measurement and adjustment to complete the component initial alignment.
- Through smooth alignment achieve the positional accuracy requirement.

Initial alignment



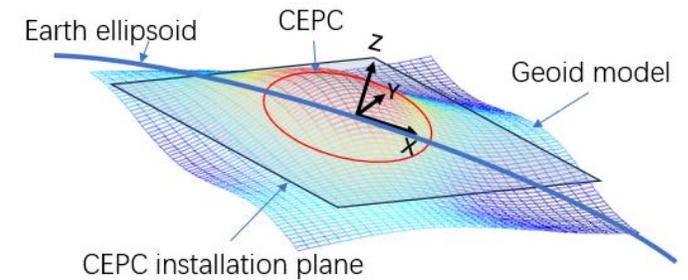
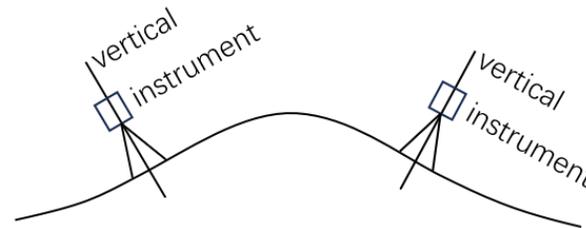
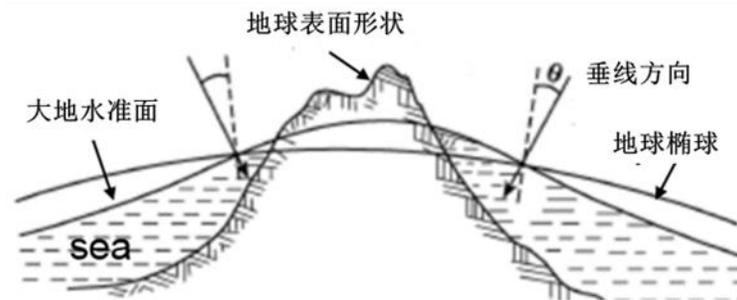
Smooth alignment



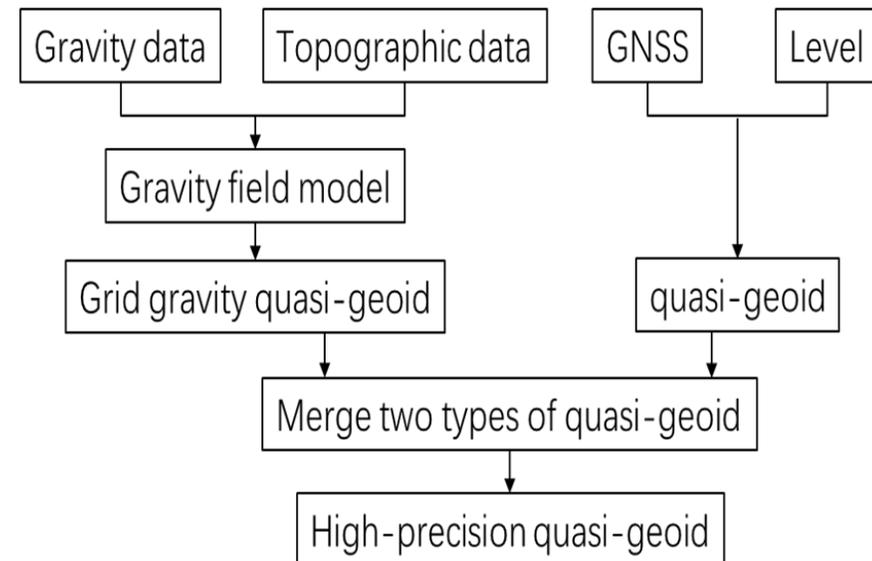
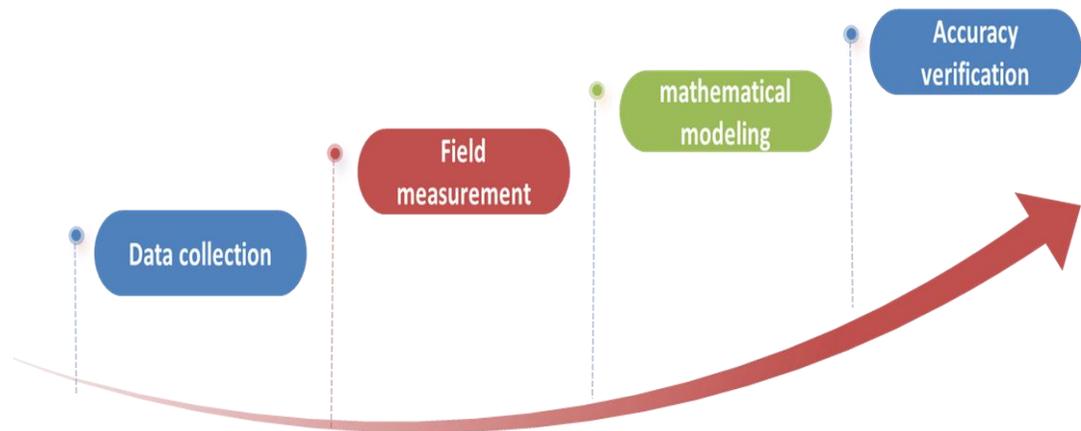
# **Alignment and installation study progress**

# 1、Geoid refinement

- Geoid refinement goal: To build a quasi-geoid model with 10mm elevation anomaly accuracy and 1" vertical deflection accuracy.



- Geoid refinement plan

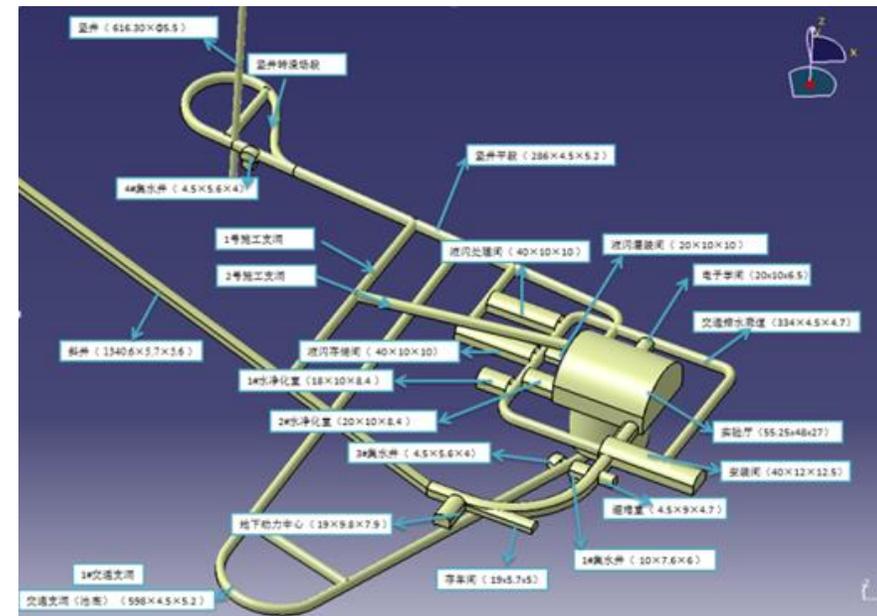


# 1、Geoid refinement

- The quasi-geoid model is based on the ground measurement data and needs to research how to transfer it to the tunnel elevation.
- We plan to select an underground space to conduct a modeling experiment.

Jiangmen Underground Neutrino Experiment  
(JUNO)

- The elevation from ground to the experimental hall is more than 550m. This big elevation is helpful to create an obvious difference between the ground model and underground model and is conducive to validate the modeling scheme.



# 1、 Geoid refinement

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- Technical route
  - Use global gravity field model to determine the medium to long wavelength signals of the local gravity field;
  - Use the ground and underground gravity data along with high resolution topographic data to determine the (very) short wavelength signals of the local gravity field;
  - Apply remove-restore method while considering the influence of the upper mass to study refined modeling technique for the underground gravity field.
  - Utilize gravity and astronomical geodetic measuring data to verify the model accuracy.

# 1、 Geoid refinement

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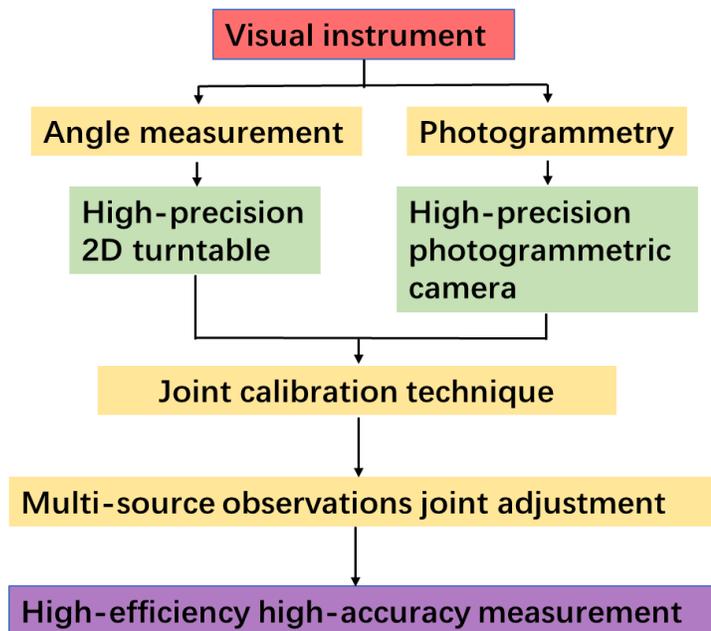
- Experimental site survey
  - We have conducted an experimental site survey in Dec. 2024.
  - The purpose includes: investigate the geological density; measure a few gravity data used for the geological density error correction; assess the feasibility of conducting gravity and astronomical geodetic measurement and prepare for make the experimental plan.



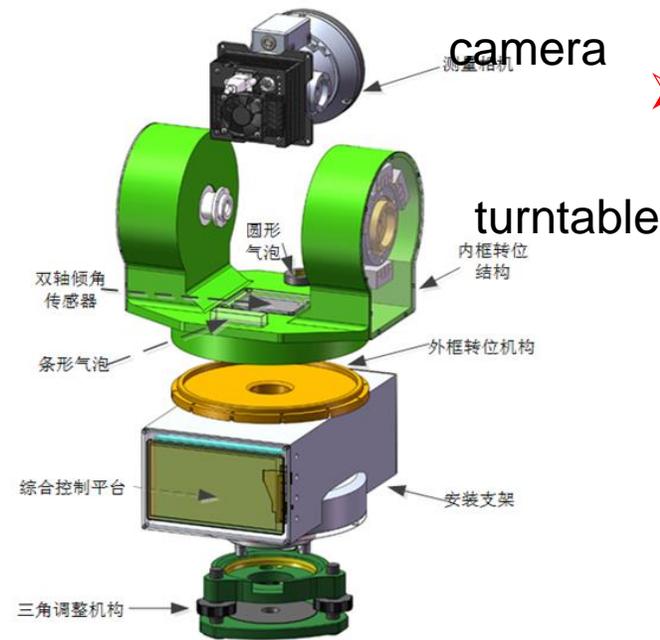
## 2、 Visual instrument

- Visual instrument R&D

- The existing measurement plan (using laser tracker) will consume a lot of manpower and time. We hope to R&D more efficient measuring instruments.



Technical route



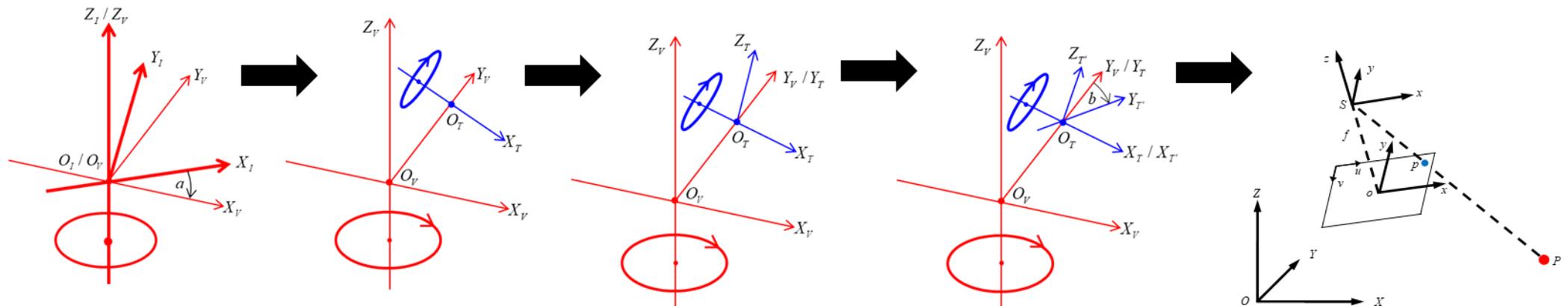
Visual instrument structure

- Collaborating with PRODETEC company, a prototype has been developed.



## 2、 Visual instrument

- Visual instrument calibration progress
  - In the assembly process, there will be non-orthogonality errors and offset errors among the turntable horizontal axis, vertical axis and the camera's optical axis. It is necessary to establish a mathematical model for the observations while taking these errors into account and calibrate these errors.



Instrument  
coordinate system

vertical axis  
coordinate  
system

horizontal axis  
static state  
coordinate system

horizontal axis  
dynamic state  
coordinate system

Camera  
coordinate system

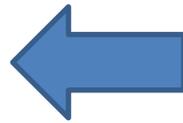
## 2、 Visual instrument

- Complete the observation error model establishment. (Wang tong)

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = R_{IC} \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} + T_{IC} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} + \begin{bmatrix} r_{14} \\ r_{24} \\ r_{34} \end{bmatrix}$$

↑  
**Camera  
coordinate  
system**

↑  
**Instrument  
coordinate  
system**



$$\left\{ \begin{array}{l} r_{11} = \cos \kappa \cos \varphi \cos \gamma \cos a - [\cos \kappa \sin \varphi \sin(b - \omega) - \sin \kappa \cos(b - \omega)] \cdot \sin a + [\cos \kappa \sin \varphi \cos(b - \omega) + \sin \kappa \sin(b - \omega)] \cdot \sin \gamma \cos a \\ r_{12} = -\cos \kappa \cos \varphi \cos \gamma \sin a - [\cos \kappa \sin \varphi \sin(b - \omega) - \sin \kappa \cos(b - \omega)] \cdot \cos a - [\cos \kappa \sin \varphi \cos(b - \omega) + \sin \kappa \sin(b - \omega)] \cdot \sin \gamma \sin a \\ r_{13} = \cos \kappa \cos \varphi \sin \gamma - [\cos \kappa \sin \varphi \cos(b - \omega) + \sin \kappa \sin(b - \omega)] \cdot \cos \gamma \\ r_{21} = \sin \kappa \cos \varphi \cos \gamma \cos a - [\sin \kappa \sin \varphi \sin(b - \omega) + \cos \kappa \cos(b - \omega)] \cdot \sin a + [\sin \kappa \sin \varphi \cos(b - \omega) - \cos \kappa \sin(b - \omega)] \cdot \sin \gamma \cos a \\ r_{22} = -\sin \kappa \cos \varphi \cos \gamma \sin a - [\sin \kappa \sin \varphi \sin(b - \omega) + \cos \kappa \cos(b - \omega)] \cdot \cos a - [\sin \kappa \sin \varphi \cos(b - \omega) - \cos \kappa \sin(b - \omega)] \cdot \sin \gamma \sin a \\ r_{23} = \sin \kappa \cos \varphi \sin \gamma - [\sin \kappa \sin \varphi \cos(b - \omega) - \cos \kappa \sin(b - \omega)] \cdot \cos \gamma \\ r_{31} = -\sin \varphi \cos \gamma \cos a - \cos \varphi \sin(b - \omega) \sin a + \cos \varphi \cos(b - \omega) \sin \gamma \cos a \\ r_{32} = \sin \varphi \cos \gamma \sin a - \cos \varphi \sin(b - \omega) \cos a - \cos \varphi \cos(b - \omega) \sin \gamma \sin a \\ r_{33} = -\sin \varphi \sin \gamma - \cos \varphi \cos(b - \omega) \cos \gamma \\ r_{14} = d \cdot [\cos \kappa \cdot \sin \varphi \cdot \sin(b - \omega) - \sin \kappa \cdot \cos(b - \omega)] + t_x \\ r_{24} = d \cdot [\sin \kappa \cdot \sin \varphi \cdot \sin(b - \omega) + \cos \kappa \cdot \cos(b - \omega)] + t_y \\ r_{34} = d \cdot \cos \varphi \cdot \sin(b - \omega) + t_z \end{array} \right.$$

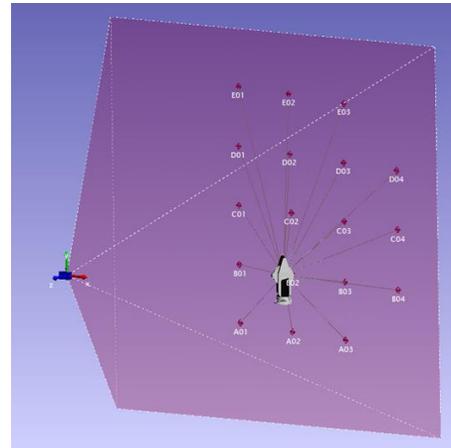
**Matrix elements containing error parameters**

## 2、 Visual instrument

- Performed the turntable axis system error calibration by a CMM .



- Conducted the camera and turntable axis system error calibration in a calibration room .



## 2、Visual instrument

- A preliminary calibration result has been obtained.

Camera pose parameters in the horizontal axis coordinate system

k/ rad	-0.0055892
$\varphi$ / rad	-0.0001756
w/ rad	0.0008046
tx/mm	-0.045
ty/mm	-0.026
tz/mm	10.661

- The offset between the horizontal axis and the vertical axis is 0.0036mm, Orthogonality error is 36.4"

- Next we will try to use a total least-squares self-calibration model to conduct a more accurate calibration.

$$\alpha_{(G,H)} = \arctan \frac{Y'_{(G,H)}}{X'_{(G,H)}}$$

$$\beta_{(G,H)} = \arccos \frac{Z'_{(G,H)}}{\sqrt{X'^2_{(G,H)} + Y'^2_{(G,H)} + Z'^2_{(G,H)}}}$$

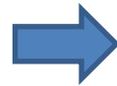
像点角度与相机坐标系的关系

$$\begin{bmatrix} X'_{(G,H)} \\ Y'_{(G,H)} \\ Z'_{(G,H)} \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} X_{(G,H)} \\ Y_{(G,H)} \\ Z_{(G,H)} \end{bmatrix} + \begin{bmatrix} r_{14} \\ r_{24} \\ r_{34} \end{bmatrix}$$

相机坐标系与视觉仪坐标系的关系

$$\begin{bmatrix} X_{(G,H)} \\ Y_{(G,H)} \\ Z_{(G,H)} \end{bmatrix} = R^T_{(G,H)} \begin{bmatrix} X'_{(G,H)} - X_l \\ Y'_{(G,H)} - Y_l \\ Z'_{(G,H)} - Z_l \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \begin{bmatrix} X_p - X_l \\ Y_p - Y_l \\ Z_p - Z_l \end{bmatrix}$$

视觉仪坐标系与全局坐标系的关系

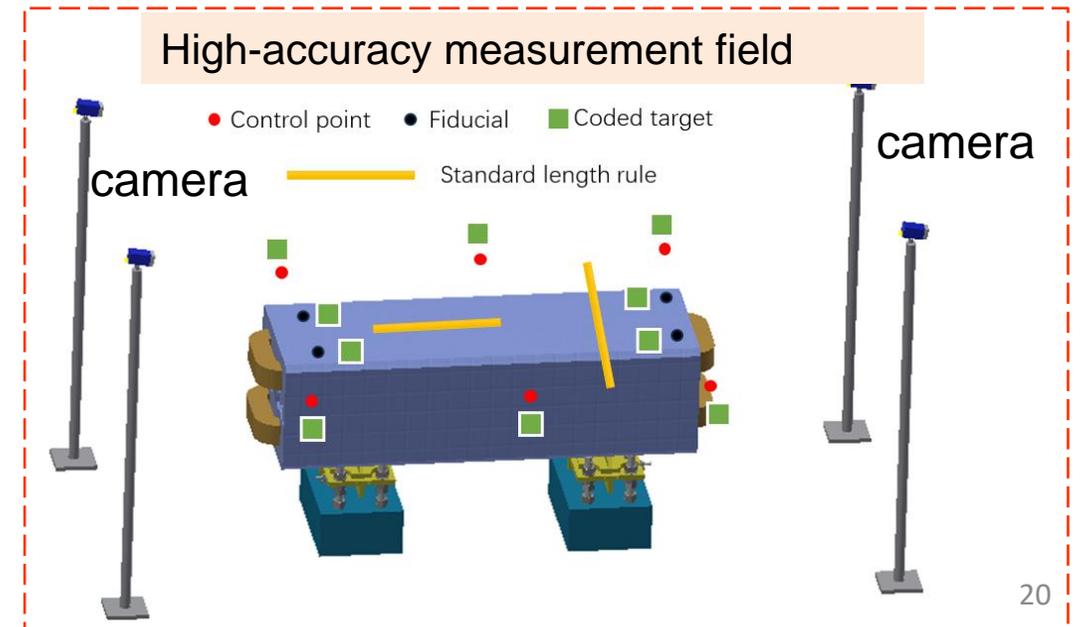


$$V = B\hat{x} - l$$

$$B = \begin{bmatrix} \frac{\partial \alpha_{(G,H)}}{\partial X_p} & \frac{\partial \alpha_{(G,H)}}{\partial Y_p} & \frac{\partial \alpha_{(G,H)}}{\partial Z_p} & \frac{\partial \alpha_{(G,H)}}{\partial X_l} & \frac{\partial \alpha_{(G,H)}}{\partial Y_l} & \frac{\partial \alpha_{(G,H)}}{\partial Z_l} & \frac{\partial \alpha_{(G,H)}}{\partial a_1} & \frac{\partial \alpha_{(G,H)}}{\partial a_2} & \frac{\partial \alpha_{(G,H)}}{\partial a_3} & \frac{\partial \alpha_{(G,H)}}{\partial b_1} & \frac{\partial \alpha_{(G,H)}}{\partial b_2} & \frac{\partial \alpha_{(G,H)}}{\partial b_3} & \frac{\partial \alpha_{(G,H)}}{\partial c_1} & \frac{\partial \alpha_{(G,H)}}{\partial c_2} & \frac{\partial \alpha_{(G,H)}}{\partial c_3} \\ \frac{\partial \beta_{(G,H)}}{\partial X_p} & \frac{\partial \beta_{(G,H)}}{\partial Y_p} & \frac{\partial \beta_{(G,H)}}{\partial Z_p} & \frac{\partial \beta_{(G,H)}}{\partial X_l} & \frac{\partial \beta_{(G,H)}}{\partial Y_l} & \frac{\partial \beta_{(G,H)}}{\partial Z_l} & \frac{\partial \beta_{(G,H)}}{\partial a_1} & \frac{\partial \beta_{(G,H)}}{\partial a_2} & \frac{\partial \beta_{(G,H)}}{\partial a_3} & \frac{\partial \beta_{(G,H)}}{\partial b_1} & \frac{\partial \beta_{(G,H)}}{\partial b_2} & \frac{\partial \beta_{(G,H)}}{\partial b_3} & \frac{\partial \beta_{(G,H)}}{\partial c_1} & \frac{\partial \beta_{(G,H)}}{\partial c_2} & \frac{\partial \beta_{(G,H)}}{\partial c_3} \end{bmatrix}$$

### 3、 High-accuracy measurement field

- Automatic adjustment technology research
  - CEPC has a large number of magnets need to be aligned. We hope to realize automatic adjustment to improve alignment efficiency.
  - Alignment team collaborates with the mechanical team. Alignment team is responsible for developing a high-accuracy measurement field for measuring the component position, output the deviation between the actual and nominal position.
  - The main structure is a multi-camera photogrammetric system, combined with a synchronization control system, a software, some base part and auxiliary equipment.



### 3、 High-accuracy measurement field

- Development progress

- A camera was developed and the testing and calibration are ongoing.



Item	Parameter
Sensor	CMOS, NOIP1SE025KA-GDI25;
Resolution	5120×5120;
Pixel size	4.5μm×4.5μm;
Sensor size	23.04mm×23.04mm;
Exposure	Exposure time 1μs ~ 1s/frame rate;
Focus	21mm;
Angle of view	47.6° ×47.6° ;
Measuring range	1~35m;
Precision	3μm+3μm/m ;

- A multichannel synchronization controller was developed. Some auxiliary equipment were purchased



### 3、 High-accuracy measurement field

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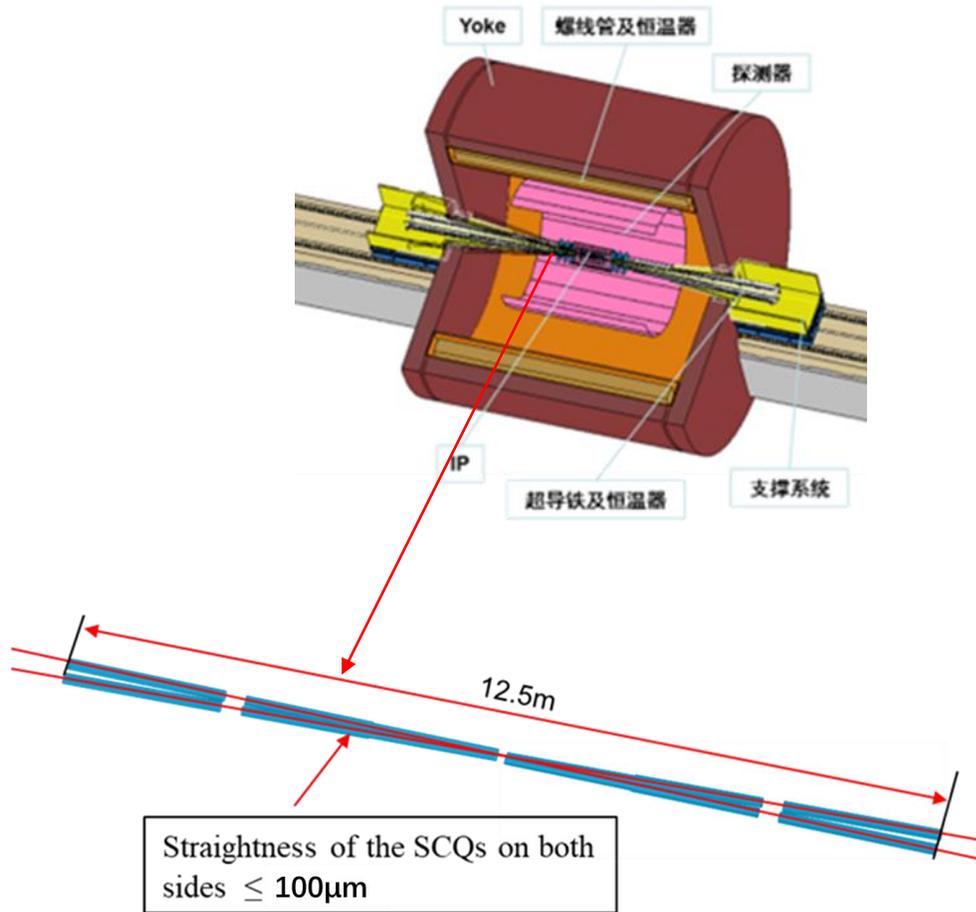
- Procured a batch of benchmark scales and photogrammetric targets.



- A software which integrated photogrammetric function, communication function, data processing, display and output functions is under development, 70% programming work is completed.
- We plan to start the high-accuracy measurement field integration and testing work in March 2025.

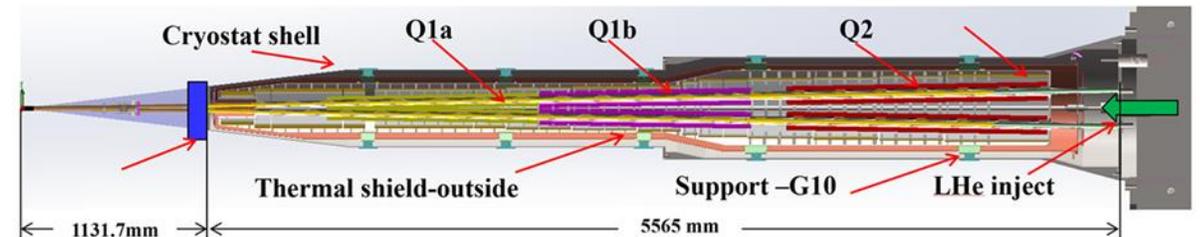
# 4、MDI alignment

- MDI alignment research



- Alignment scheme

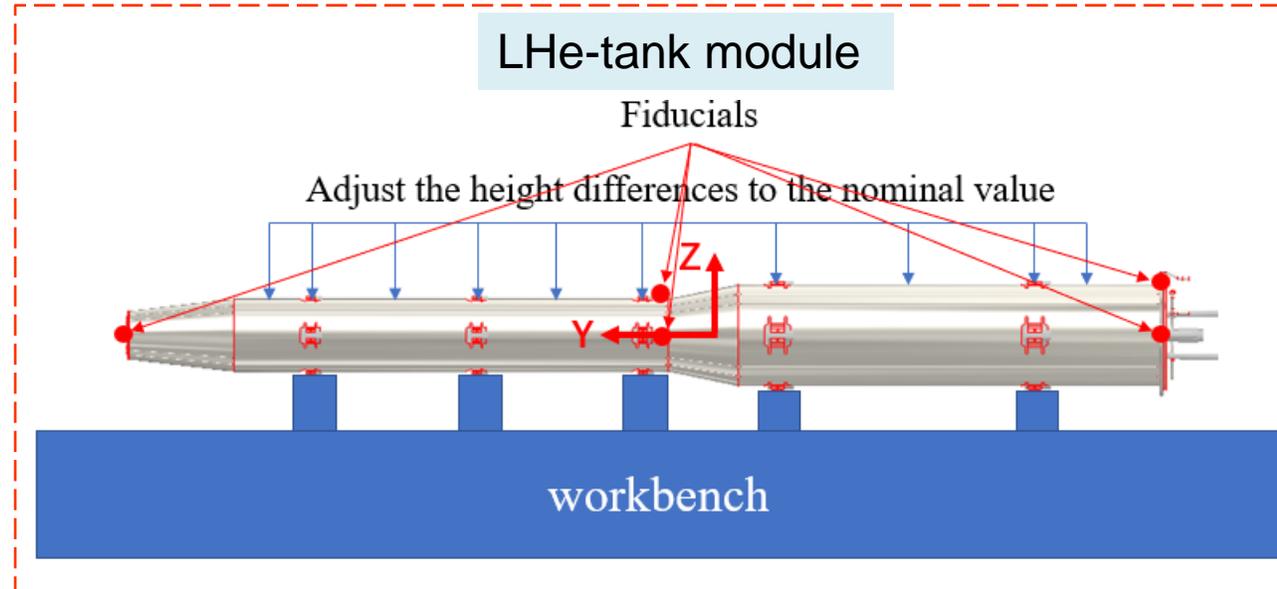
- a) LHe-tank module fiducialization
- b) Cryostat pre-alignment
- c) Cryostat installation alignment



## 4、MDI alignment

### a) LHe-tank module fiducialization

- Q1a, Q1b, Q2, anti-solenoids are fixed together with the LHe-tank by a skeleton .

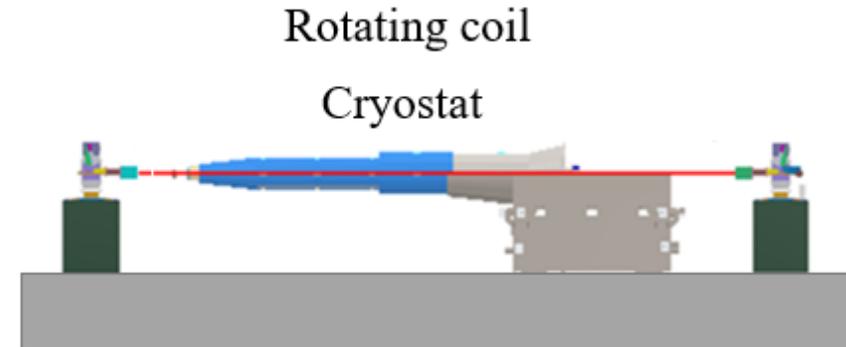
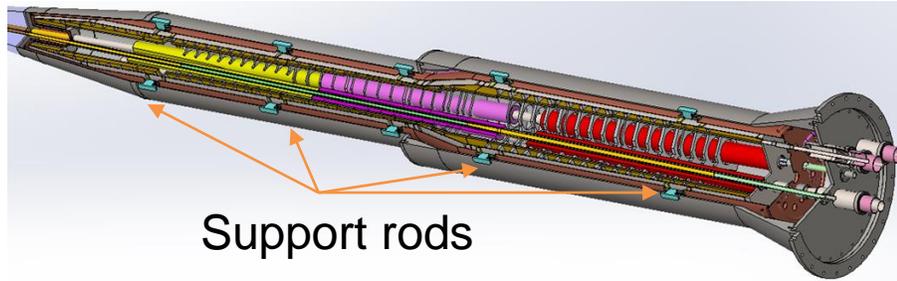


- The LHe-tank module should be placed on a workbench and properly supported to prevent deformation.
- Making a fiducialization of the module to record the coordinates of the fiducials in this state.

## 4、MDI alignment

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### b) Cryostat pre-alignment



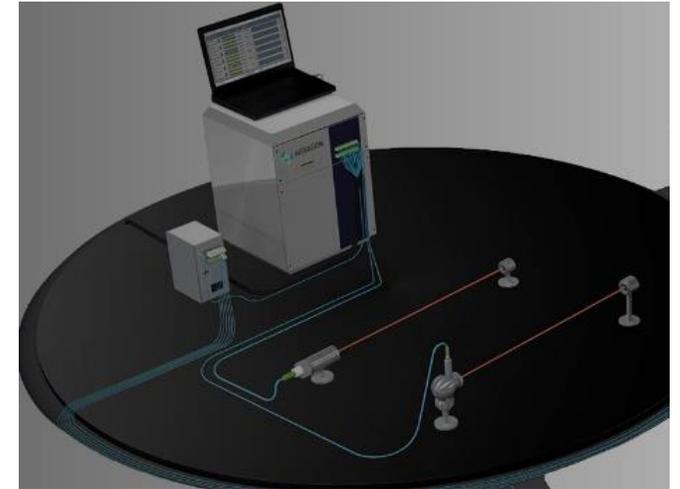
- After the cryostat is installed on the support, due to the cantilever structure, the LHe-tank module will occur deformation. Restore the shape of the LHe-tank module according to the fiducialization coordinates of the fiducials by adjusting the support rods.
- After restore the shape of LHe-tank module, performing the SCQ magnetic center measurement by a rotating coil, and relate the magnetic center to the fiducials on the outside of the cryostat.



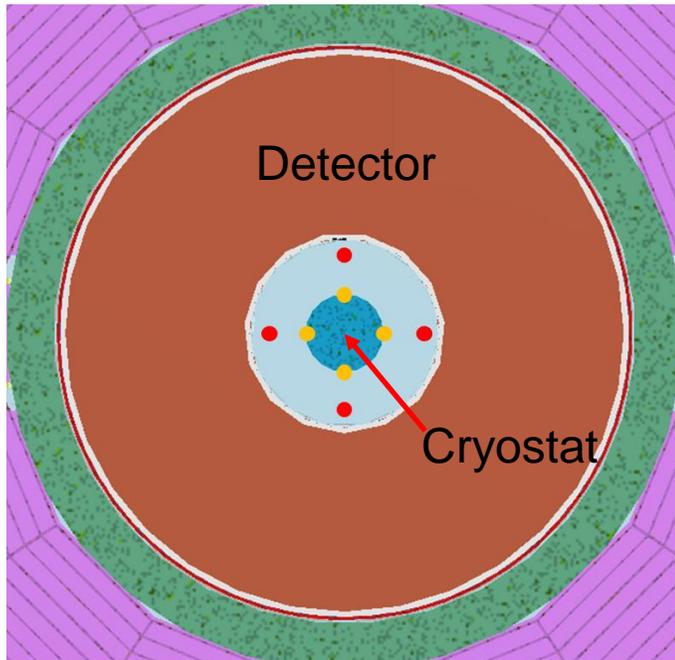
# 4、MDI alignment

- Possible method
  - Using a Multiline laser ranging system to monitor the cryostat front end position.

Multiline laser ranging system



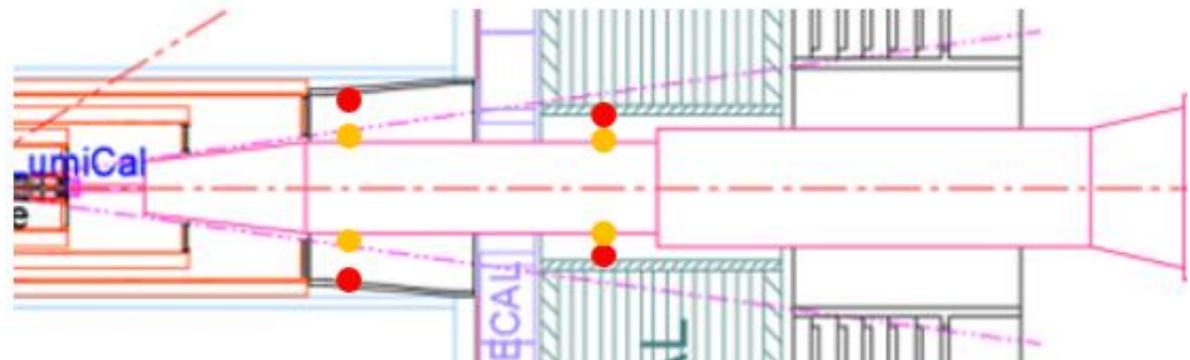
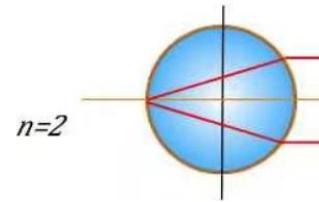
- Laser collimator
- High index glass target



Laser collimator

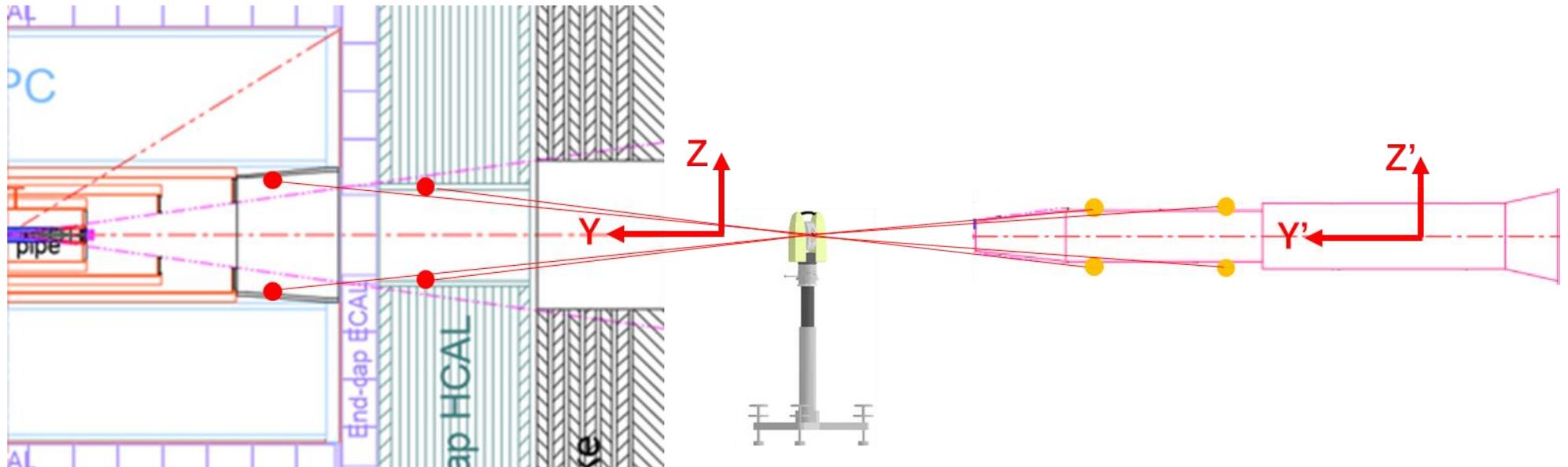


High index glass target



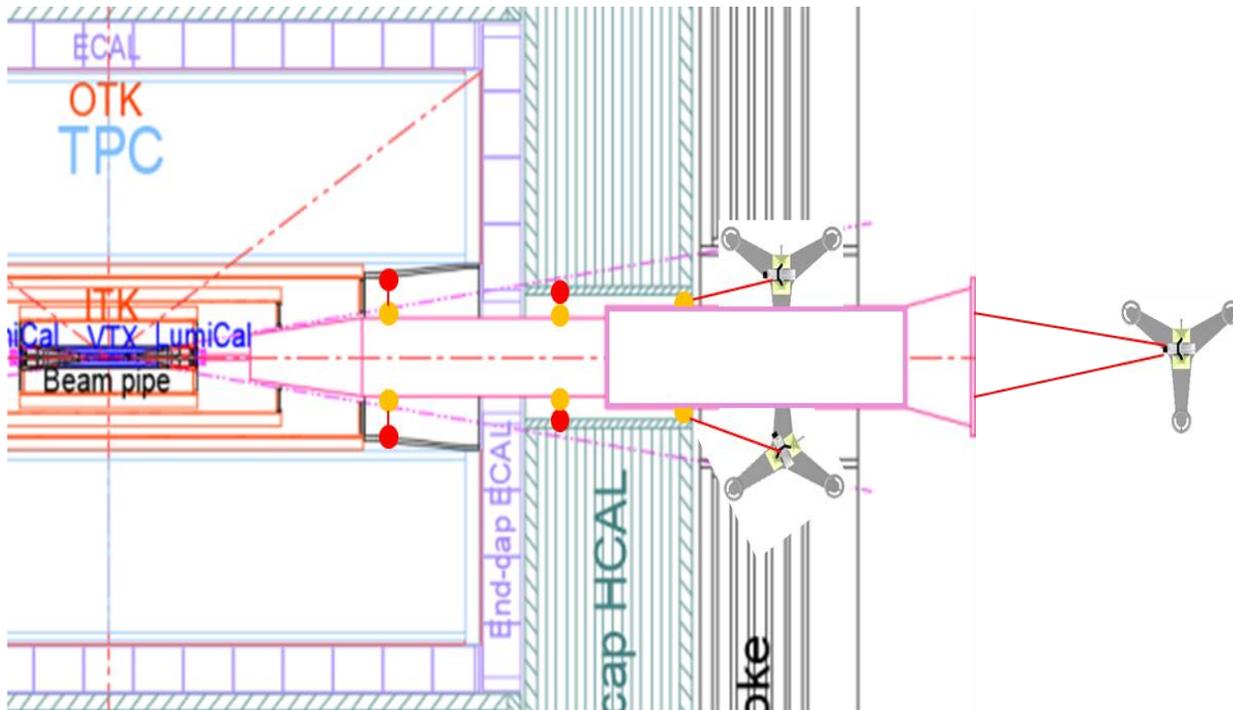
## 4、 MDI alignment

- Before the cryostat is pushed into the detector, use a laser tracker measure the coordinates of these points.
- Calculate the nominal coordinates of these glass targets when the cryostat is pushed to the design position in the detector.
- Thus, we can obtain the nominal distance values between these laser collimators and the nominal coordinates of their corresponding targets.



## 4、MDI alignment

- After the cryostat is pushed into the detector, jointly apply Multiline laser ranging system and laser trackers to measure its position and align it accurately.



### Error analysis

Error item	Error / $\mu\text{m}$
SCQs installation in skeleton	50
LHe-tank module fiducialization	30
Cryostat module pre-alignment	50
Laser alignment system	20
Multiline & Laser tracker measurement	30
Cryostat module adjustment	30
<b>Total</b>	<b>90</b>

# 5、 Installation shceme

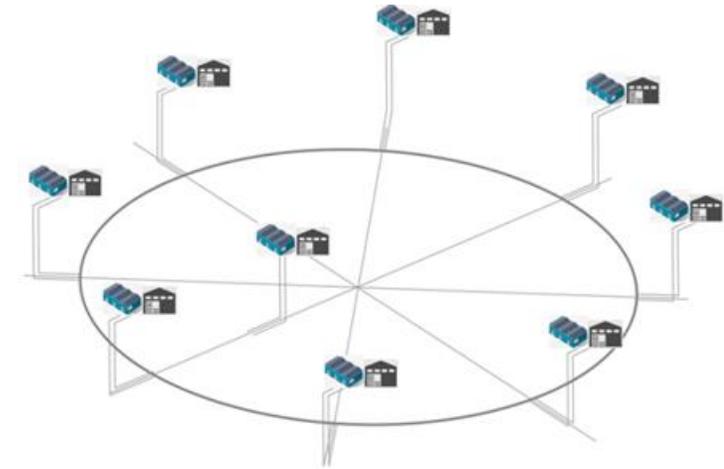
- Surface test hall and warehouse layout



Test hall



Warehouse



- Ring installation schedule: 3 years and 9 months

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								
44	Network construction	█	█	█	█	█	█	█																																														
32	Network measurement		█	█	█	█	█	█																																														
32	Support setting out								█	█																																												
16	Support setting out									█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█			
40	Support installation								█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█		
32+32	Ring installation									█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█		
16	Smooth alignment																																																					
64	Smooth alignment																																																					

# Summary

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- As part of the geoid refinement study, we plan to conduct an underground modeling technique study. An experimental site has been selected, and field survey has been performed.
- To improve measurement efficiency, a visual instrument R&D is conducted. The calibration study is in progress.
- To achieve automated alignment adjustments of the magnets, a high-accuracy measurement field R&D is ongoing.
- A MDI alignment scheme is made.

Thank You !