High Energy Photon Source

Magnetic Center Fiducialization of HEPS Insertion Devices

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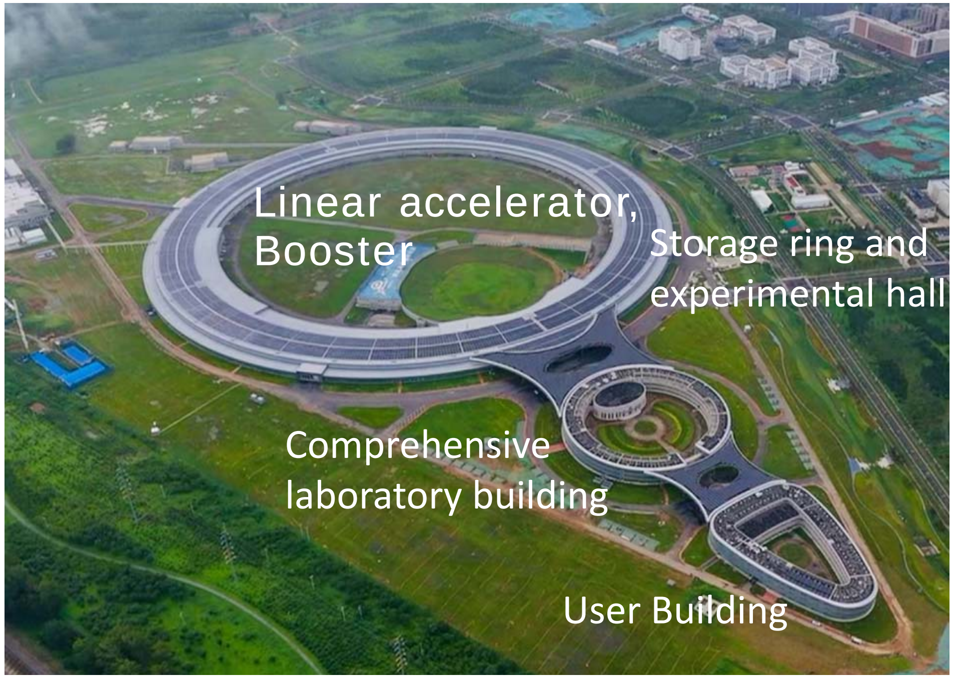


International Workshop on Accelerator Alignment 2024, Menlo Park, CA 94025 USA.

Introduction

- High Energy Photon Source(HEPS) is a high-performance and high-energy synchrotron radiation light source with a beam energy of 6GeV and an ultra-low emittance of better than 0.06nm·rad. Insertion device (ID) is a key component for HEPS synchronous light extraction. The HEPS construction phase 1 involves installing 19 insertion devices (IDs) across 14 beamlines, comprising various types such **as In-air wiggler (IAW), In-air undulator (IAU), In-vacuum undulator (IVU), Apple-Knot undulator(AK), MANGO wiggler (IAMW), and Cryogenic permanent magnet undulator (CPMU).**

- To ensure optimal synchrotron radiation performance, HEPS necessitates fiducializing ID magnetic centers with an accuracy better than **30 µm**, given the ±50 µm magnetic field region in the vertical direction. However, conventional Hall probe measurement systems used for precise magnetic field measurements cannot determine the absolute position of magnetic centers within ID. Thus, employing a Magnetic Landmark device(MLK) as a medium, combined with Laser tracker, accurately establish the positional relationship between the ID magnetic center and external fiducials, ensuring precise positioning and orientation.

HEPS single-cell layout

Insertion Device

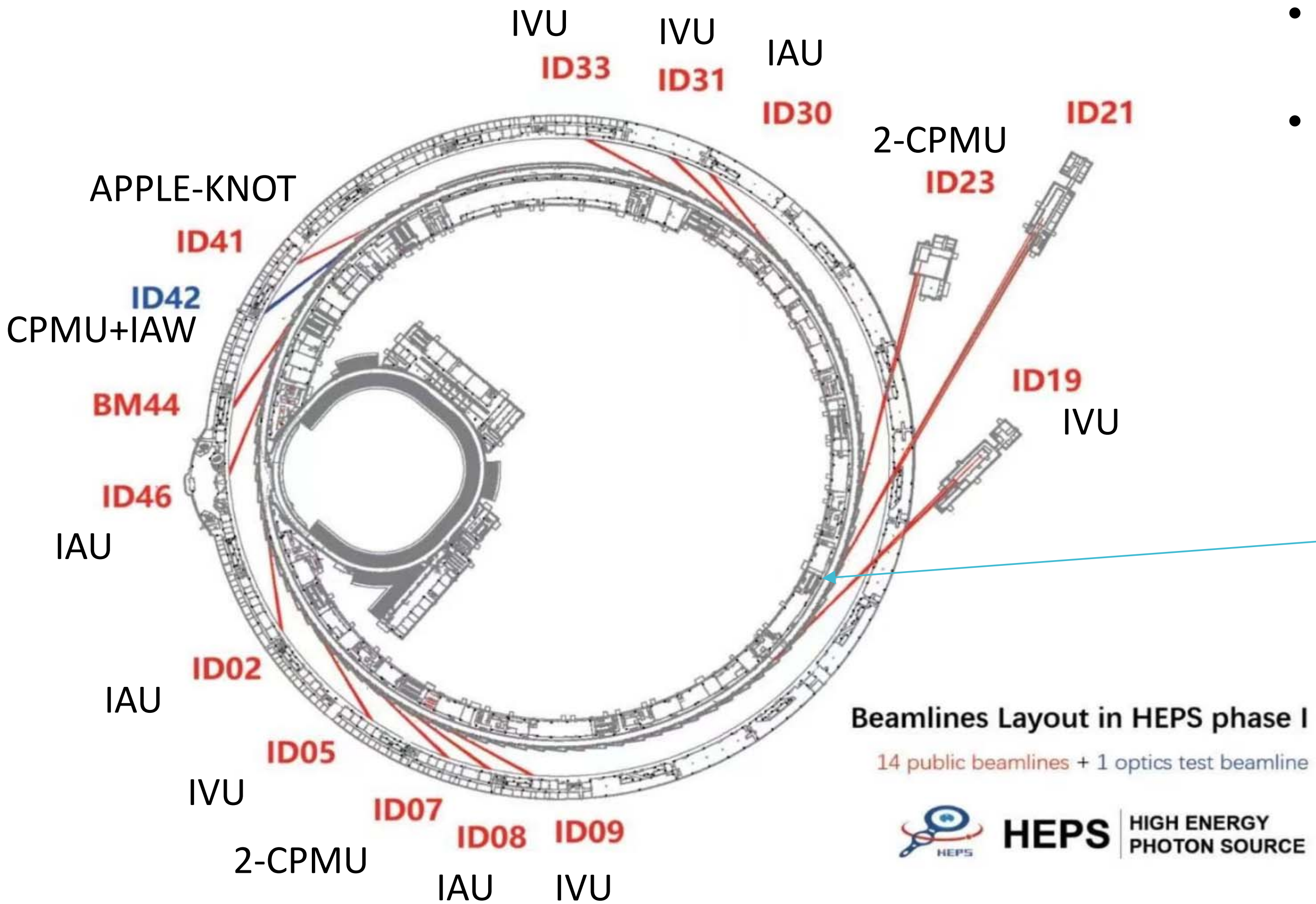
Contents

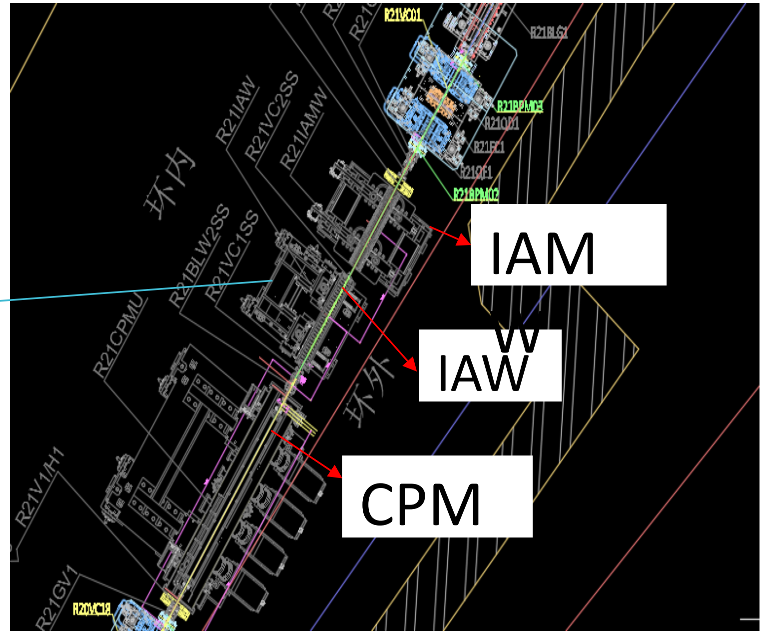
1.Distribution of Insert Devices in HEPS Storage ring

ID's type	Beamlines NO.	Name of Beamlines	ID's Length [m]
IAU	ID02(BA)	Microfocusing X-Ray Protein Crystallography Beamline	5
IVU	ID05(B9)	Low-Dimensional Structure Probe Beamline	4
CPMU+CPMU	ID07(B1)	Engineering Materials Beamline	2+2
IAU	ID08(BB)	Pink Beam SAXS Beamline	5
IVU	ID09(B4)	Hard X-Ray Coherent Scattering Beamline	4
IVU	ID19(B2)	Hard X-Ray Nanoprobe Multimodal Imaging Beamline	4
CPMU+IAW+Mango Wiggler	ID21(B7)	Hard X-Ray Imaging Beamline	2+1+1
CPMU+CPMU	ID23(B3)	Structural Dynamics Beamline	2+2
IAU	ID30(BE)	Transmission X-Ray Microscopic Beamline	5
IVU	ID31(B6)	High Pressure Beamline	4
IVU	ID33(B5)	Hard X-Ray High Resolution Spectroscopy Beamline	4
APPLE-KNOT	ID41(BC)	High Resolution Nanoscale Electronic Structure Spectroscopy Beamline	5
CPMU+IAW	ID42(BF)	Optics Test Beamline	2+1
IAU	ID46(B8)	X-Ray Absorption Spectroscopy Beamline	5

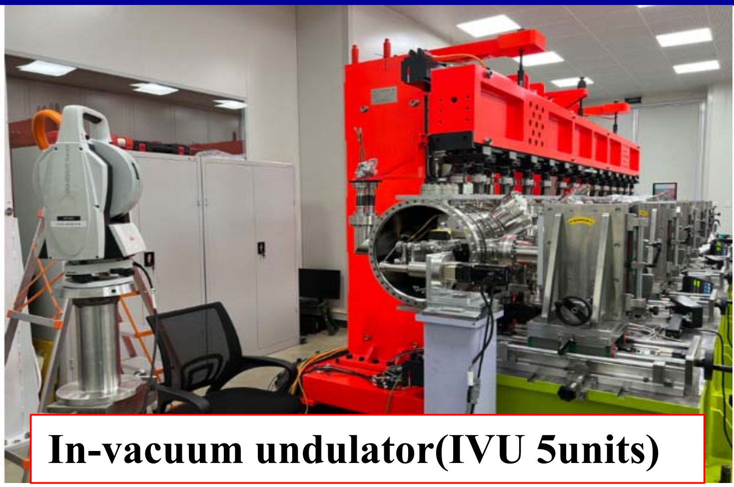
1. Distribution of Insert Devices in HEPS Storage ring

- ID21 is the longest beamline station with a length of 300 meters.
- Three IDs were designed at ID21, namely CPMU, IAW, and IAMW





2. Type of HEPS Insertion Devices



In-vacuum undulator(IVU 5units)

In-air undulator (IAU 4units)

In-air wiggler(IAW 2units)

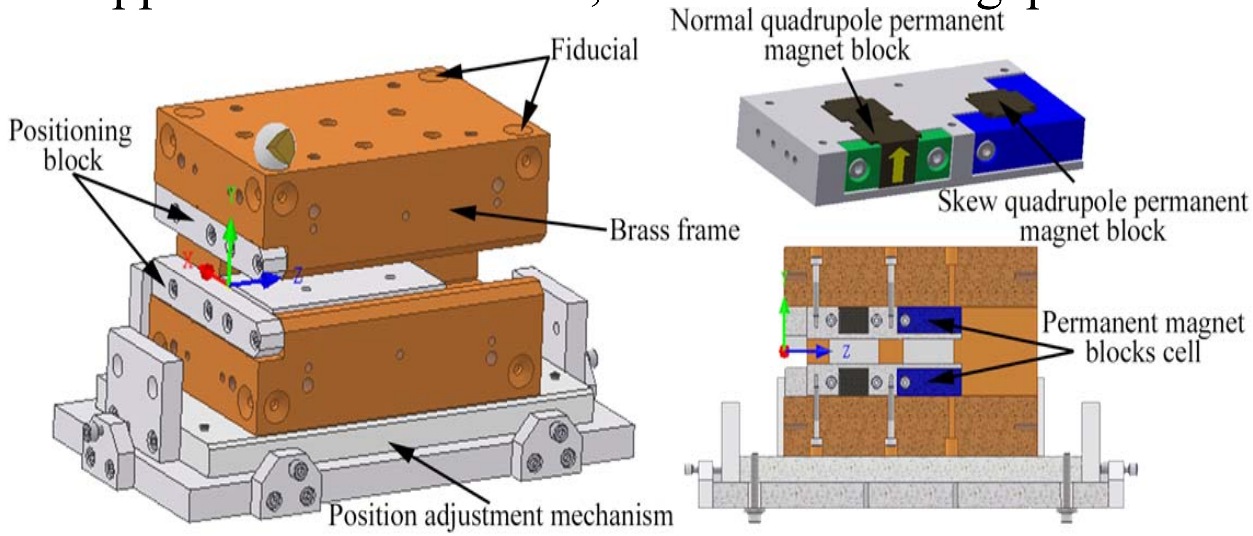
Cryogenic permanent magnet undulator(CPMU 6units)

Apple-Knot undulator(AK 1unit)

MANGO wiggler(IAMW 1unit

2.The design of the Magnetic Landmark

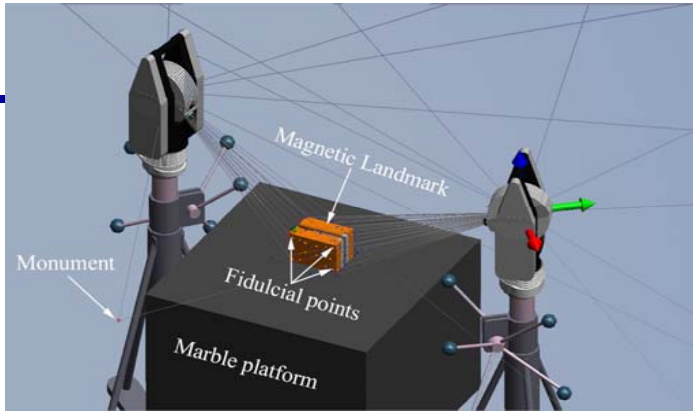
- We used the magnetic Landmark (MLK) with similar structures to European XFEL and Shanghai Light Source SSRF
- The permanent magnet blocks are constructed from **neodymium iron boron** with a remanence of 1.26T, exhibiting robust magnetic properties. within a vertically symmetrical plane.
- Each permanent magnet block : 20mm(length) × 20mm (width)× 16mm(height).
- The vertical gap of 20mm between the upper and lower blocks, and a horizontal gap of 30mm between the left and right blocks.
- The four permanent magnet blocks on the left side generate a normal quadrupole magnetic field



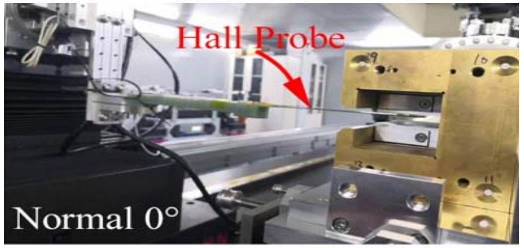
3.Self-Fiducialization of the MLK

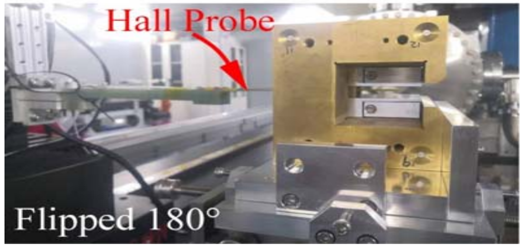
• Mechanical center fiducialization of the MLK

We use the laser tracker AT960 to perform mechanical center calibration on MLK. This procedure establishes a mechanical center coordinate system, with the coordinate origin positioned on one end face of the MLK. The Z-axis of this coordinate system coincides with the line connecting the geometric centers of the normal and skew quadrupole permanent magnet blocks, while the Y-axis is perpendicular and points upwards, forming a right-handed coordinate system along with the X-axis.



Mechanical center fiducialization





Magnetic Center fiducialization

• Magnetic Center fiducialization of the MLK

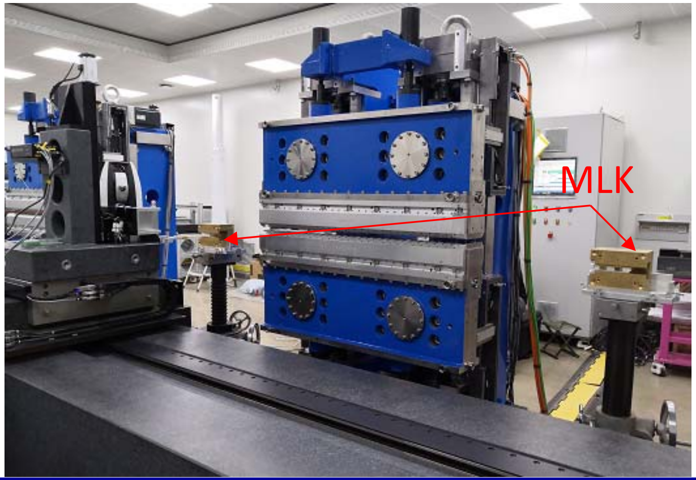
The principle of flip measurement is used to obtain the deviations between the zero points of the normal and skew quadrupole magnetic fields and the mechanical center. Then, the spatial relationship between the two magnetic field zero points of the MLK and the external fiducials is established, thereby achieving the fiducialization of the magnetic center of the MLK

See the article for details: ***The Design and Application of Magnetic Landmark used for Magnetic Fiducialization of HEPS Insertion Devices,*** Lingling Men *et al* 2024 *Meas. Sci. Technol.* **35** 105002

The fiducialization process varies for different types of IDs. I will introduce them separately below. **Instrument we use： a laser tracker AT930 or AT403**

4. IAW fiducialization process

- We measure the Hall motion direction, measure the reference surfaces of the main girders, measure the IAW guide rail reference, measure the control network monuments, and measure the fiducials of the IAW.
- Establish the IAW guide rail coordinate system
- Establish the IAW marble Hall motion coordinate system
- Aligning the IAW guide rail coordinate system to the Hall coordinate system
- Aligning the MLK to the Hall coordinate system
- After scanning the MLK's field, conduct a comprehensive measurement.
- **After unifying all data in a unified coordinate system, establish the magnetic center coordinate system of the IAW** which completes the extraction of the magnetic center of the IAW.



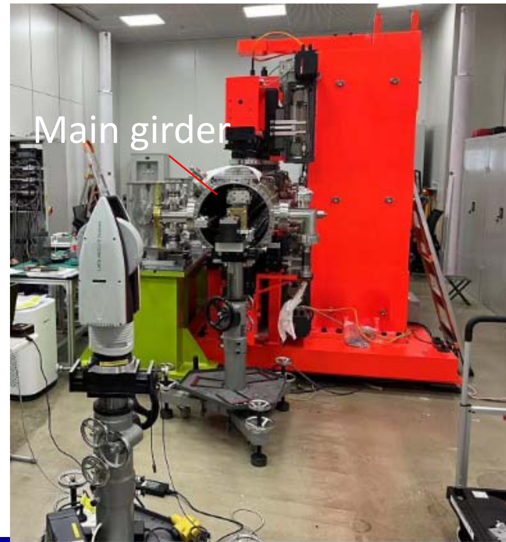
5. IVU fiducialization process

1). Adjust IVU Leveling

- Measure the control network monuments, measure the horizontal level, measure the reference surfaces of the main girders, measure the reference surfaces of the IVU`s guide rail, and measure the fiducial points of the IVU;
- Establish the level coordinate system of the IVU;
- Establish the coordinate system of the IVU column guide rail;
- Leveling the column guide rail coordinate system to the level coordinate system

2).Hall guide rail alignment

- Measure the control network monuments and the fiducials of the IVU, fit the control network into the control network under the IVU guide rail coordinate system.
- Adjust the top surface and lateral of the vacuum chamber Hall guide rail based on the control network in the strongback guide rail coordinate system.

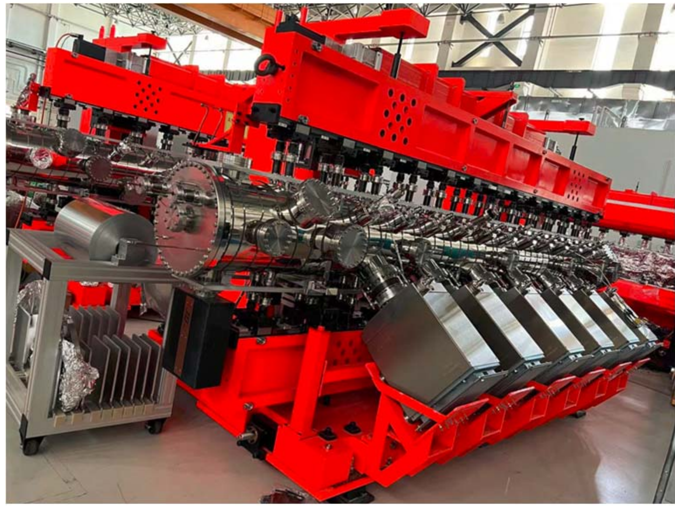


5. IVU fiducialization process

3). Calibration of IVU Hall motion coordinate system

- After the magnetic field of the insert is adjusted (completed by the magnet group), we measure the direction of the Hall movement, measure the reference surfaces of the main girder, measure the control network, and measure the fiducials of the IVU.
- Establish the IVU Hall motion coordinate system

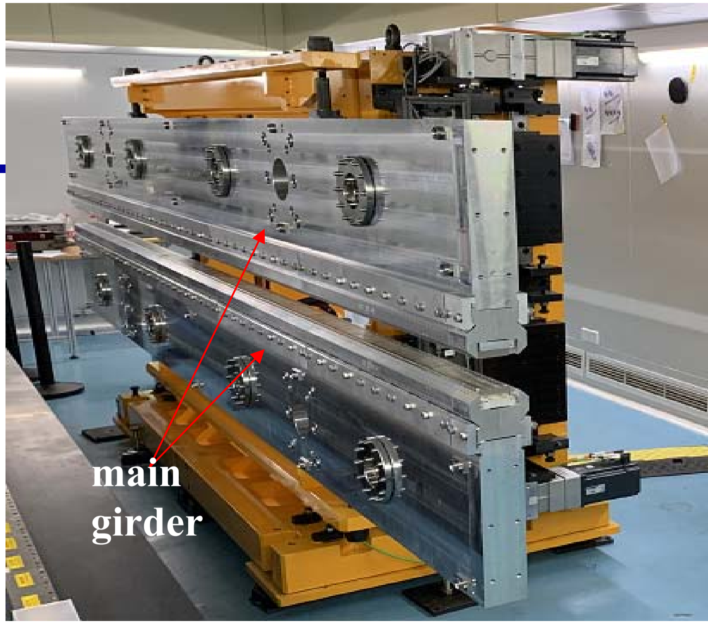
4). MLK Alignment



- Aligning the MLK at the entrance and exit ends to the Hall motion coordinate system until it is in position.
- Magnetic field scanning of the magnetic target (to be completed by the magnet group)

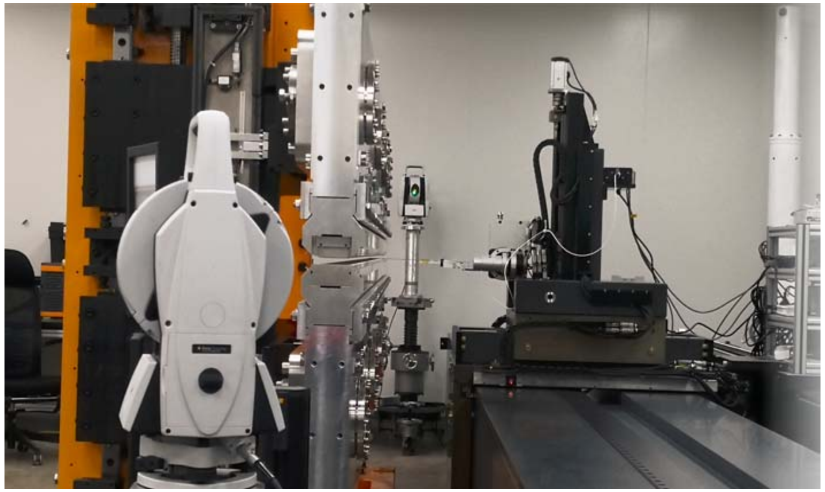
5). Comprehensive measurement and establishment of the magnetic center coordinate system

6. IAU fiducialization process



1). Leveling IAU and Establish the strongback guide rail coordinate system

2). Inspection, measurement, and adjustment of the main girders



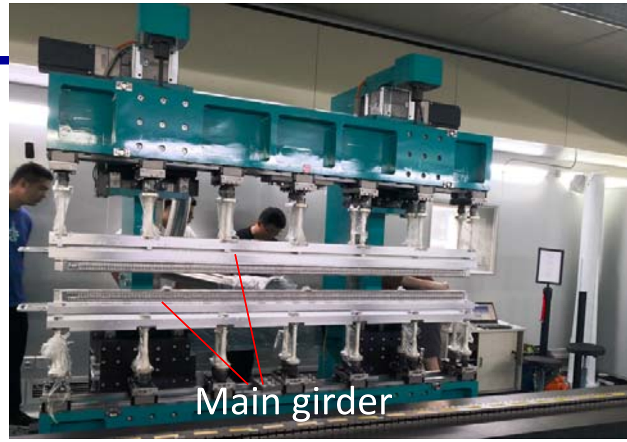
3). Calibration of the IAU Hall coordinate system

4). Align the IAU to the Hall coordinate system

5). Align the MLK to the Hall coordinate system

6). Comprehensive measurement and establish -ment of the magnetic center coordinate system

7. CPMU fiducialization process

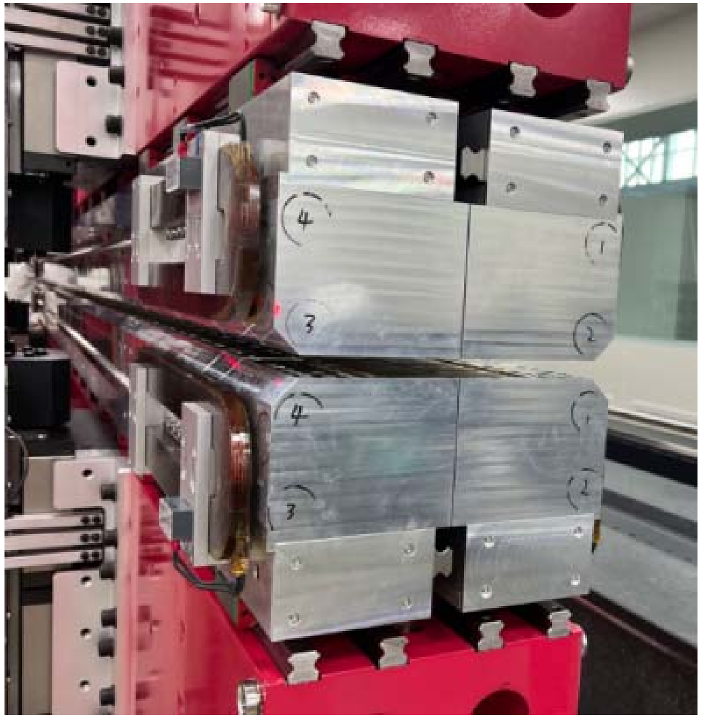


1). Adjust the CPMU to a horizontal position
2). Inspection, measurement, and adjustment of the main girders
3). Calibration of the CPMU column guide rail coordinate system and marble Hall coordinate system
4). Align the CPMU strongback guide rail coordinate system to the marble Hall coordinate system
5). Re-inspection, measurement, inspection, and adjustment of the main girders after installing the vacuum outer tube.
6). Alignment of the vacuum chamber
7). Alignment of Hall guide rail in the vacuum chamber
8). Calibration of Hall motion coordinate system in the vacuum chamber
9). Align the MLK to the Hall motion coordinate system in vacuum chamber
10). Comprehensive measurement and establishment of the magnetic center coordinate system

8. AK fiducialization process

1). Calibration of the AK and strongback guide rail coordinate system

2). Calibration of the AK and marble Hall coordinate system



3). Alignment of the AK strongback guide rail coordinate system to the marble Hall coordinate system

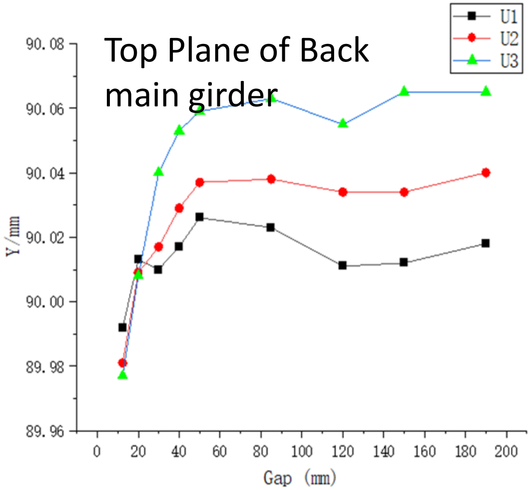
4). Align the MLK to the marble Hall coordinate system

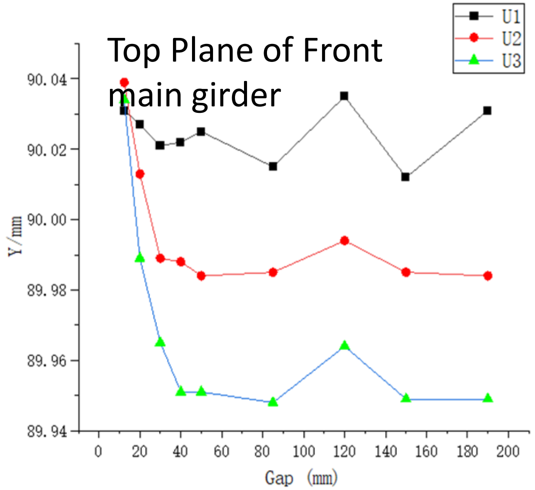
5). Comprehensive measurement and establishment of the magnetic center coordinate system.

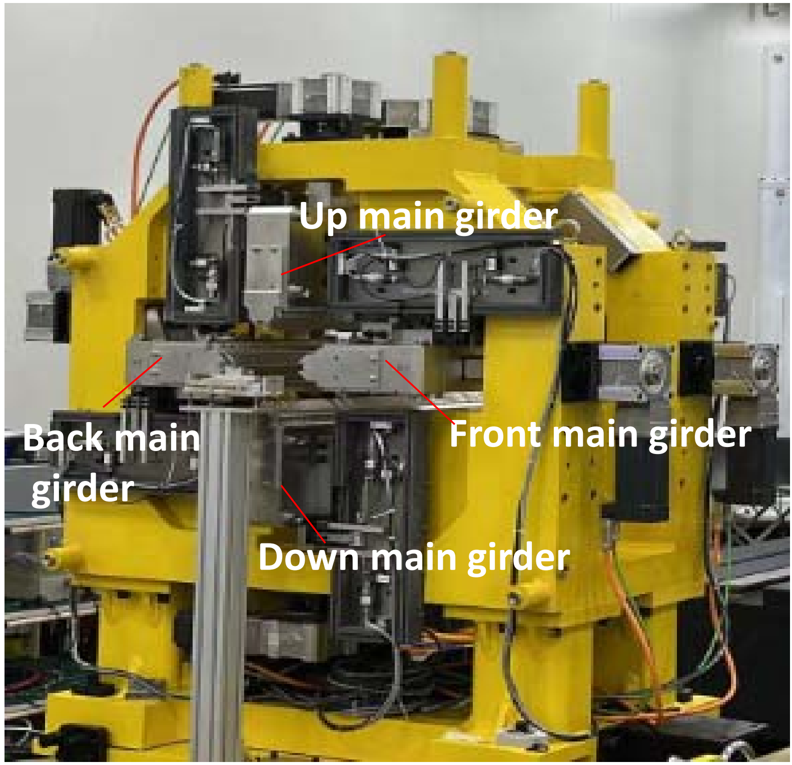
9. IAMW fiducialization process

1). Calibration of the IAMW polar head motion coordinate system

2). Adjust the parallelism and perpendicularity of the four main girders based on the motion coordinate system of the AK. Make adjustments if they exceed the tolerance limits.(less than 40 μm)







Motion gap distribution(unit:mm)								
12.4	20	30	40	50	85	120	155	190

9. IAMW fiducialization process

3). Calibration of the IAMW Hall motion coordinate system

4). Aligning Hall support rod and Hall guiding tube

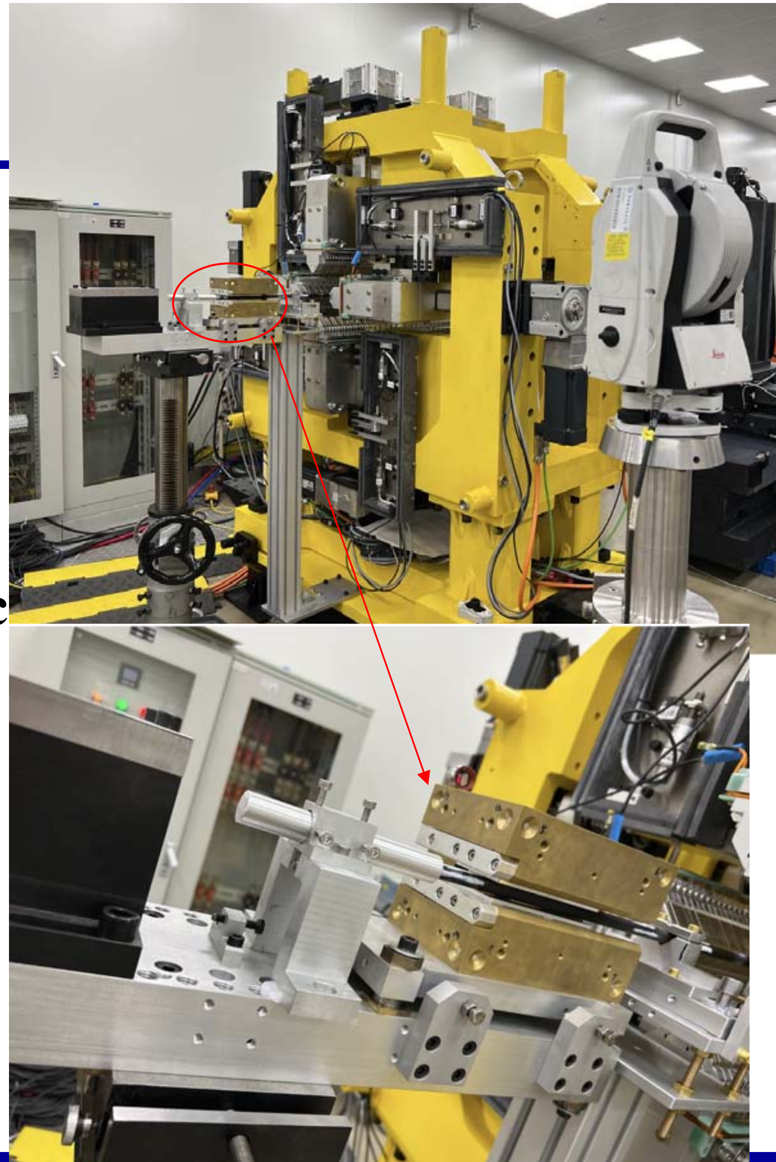
- First adjust the Hall support rod, then align it in the IAMW Hall motion coordinate system
- Using Laser tracker ,Theodolite and level instruments align the Hall guiding tube

Hall guiding tube

9. IAMW fiducialization process

5). Align the MLK to the IAMW Hall motion coordinate system

6). Comprehensive measurement and establishment of the magnetic center coordinate system



10. Accuracy analysis and data statistics

- The primary sources of error in the fiducialization process of the ID magnetic center using the MLK encompass the measurement error of the laser tracker, MLK positioning measurement error, MLK magnetic field zero point measurement error, and MLK self-fiducialization error. Utilizing observation data from 4 IDs and employing error calculation formulas (1) and (2) for the dual observation column, the root mean square errors in point measurement of the laser tracker for the *X* and *Y* coordinates of the ID are determined to be: $\sigma_x(ID) = \sigma_y(ID) = 10\mu m$.

$$\sigma_P = \sqrt{\frac{\sum_{1}^{n} d_i^2}{2n}} \quad (1)$$

d_i represents the measurement deviation of the *i*-th reference point of the MLK, *n* represents the total number of reference points of the MLK

σ_P represents the measurement error of the calibration measurement point of the MLK

$$\sigma_x = \sigma_y = \sigma_z = \sigma_P / \sqrt{3} \quad (2)$$

σ_x σ_y σ_z respectively represent the root mean square error in the X, Y, and Z unidirectional coordinates.

10. Accuracy analysis and data statistics

- **Accuracy of ID mechanical center fiducialization :** $\sigma_x(M) = \sigma_y(M) = 3\mu m$
- **Accuracy of MLK magnetic field zero-point measurement:** $\sigma_x(Zero) = 7\mu m$ $\sigma_y(Zero) = 2\mu m$
- **MLK calibration accuracy**:

$$\sigma_x(MLK) = (3^2 + 7^2 + 7^2)^{1/2}\mu m = 10\mu m \qquad \sigma_y(MLK) = (3^2 + 2^2 + 2^2)^{1/2}\mu m = 4\mu m$$

So, we calculation the accuracy of the ID magnetic center calibration :

$$\sigma_x(Mag) = (\sigma_x^2(ID) + \sigma_x^2(M) + \sigma_x^2(Zero) + \sigma_x^2(MLK))^{1/2} = 16\mu m$$

$$\sigma_y(Mag) = (\sigma_y^2(ID) + \sigma_y^2(M) + \sigma_y^2(Zero) + \sigma_y^2(MLK))^{1/2} = 11\mu m$$

10. Accuracy analysis and data statistics

Deviation of magnetic axis and mechanical axis positions at the entrance and exit ends of the IDs

ID's name	Entrance end		Exit end	
	dX/mm	dY/mm	dX/mm	dY/mm
R02IAU	-0.029	0.003	-0.002	-0.012
R08IAU	0.048	-0.018	0.050	-0.021
R30IAU	0.091	0.035	0.116	0.037
R22IAW	-0.149	-0.041	-0.150	-0.025
R42IAW	0.045	-0.019	0.025	-0.015
R07CPMU2	-0.101	-0.190	-0.080	-0.148
R09IVU	-0.006	-0.029	-0.204	-0.003
R33IVU	-0.285	-0.010	0.395	-0.009

11. Summary

- Calibration of ID is the most multiple steps in HEPS equipment, with the largest amount of data. It requires conversion between several coordinate systems, and there are many types of IDs, each with its own calibration procedure. This requires us to handle the data carefully, and standardizing the data format brings us a lot of convenience.
- Analyze the data of the calibration deviation between the mechanical axis and the magnetic axis to determine if there is any random error in the calibration process.

Thank you for your attention!