Multilateration Method for Pre-Alignment of HEPS Storage Ring

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1. Pre-alignment requirements for HEPS storage ring

- **The HEPS storage ring:**

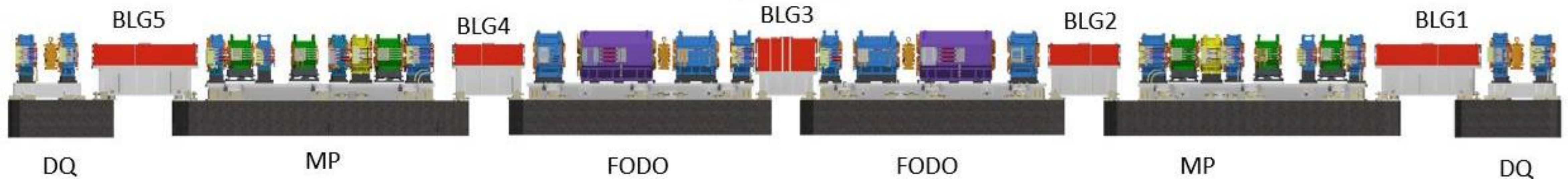
  - Circumference is about 1400 meters

  - Have 48 cells, 288 girder (98 MP, 98 FD, 98 DQ) .

- **In order to improve the installation efficiency and accuracy of the storage ring**

  -Each girder is pre-aligned in the laboratory

  -Then transported to the storage ring to participate in the tunnel alignment.



HEPS Cell

- **Based on simulation and physical design of the accelerator, the standard deviation for the pre-alignment adjustment of magnets on one girder with respect to each other in transverse and vertical must below 30μm.**

1. Pre-alignment requirements for HEPS storage ring

- **Through error analysis, the measurement accuracy of the pre-alignment is better than 10 μm. And the adjustment accuracy is better than 10 μm.**

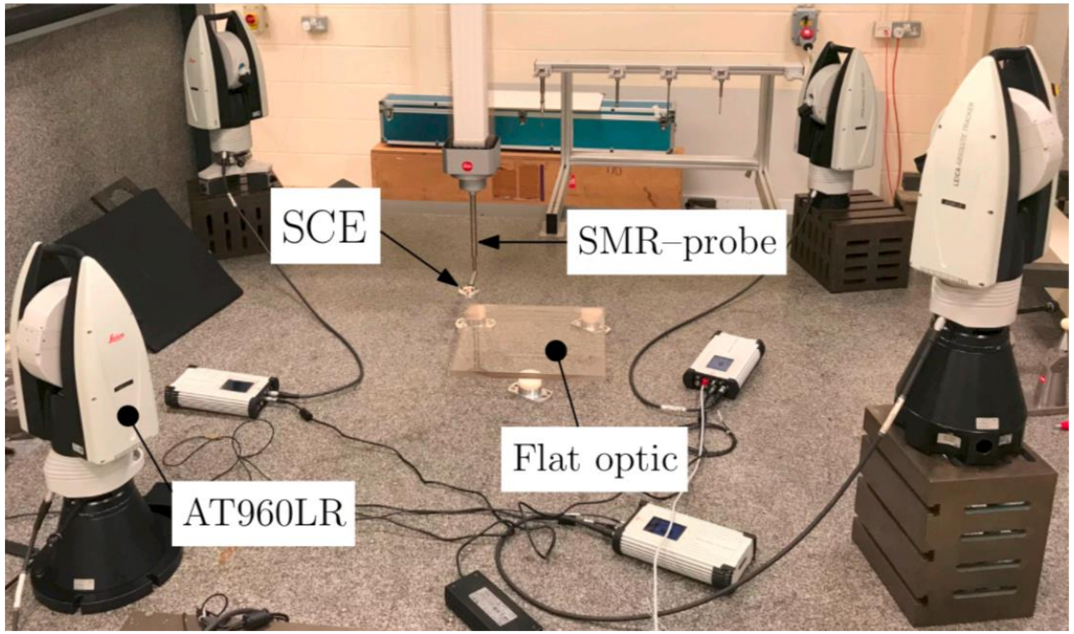
Final Accuracy /mm		**Stage Accuracy /mm**		**Fundamental accuracy /mm**	
Total	0.047	Pre-alignment	0.030	Magnetic center of magnet leads to calibration accuracy	0.010
				Measurement accuracy	0.010
				Adjustment deviation	0.015
				Magnet lock	0.010
				Magnet open and close	0.010
				Transport	0.015
				Deformation in tunnel	0.010
		Tunnel alignment	0.036	Adjustment of displacement measurement accuracy	0.005
				adjustment deviation	0.020
				Relative control measurement accuracy	0.030

2. Multilateration Measurement method

- **Due to the influence of angle measurement accuracy, the three-dimensional coordinate measurement accuracy of laser tracker reaches 15μm +6μm/m.**
- **The absolute distance measurement (ADM) accuracy of laser tracker is 10 μm over the full-scale range and the interferometer (IFM) measurement accuracy of laser tracker is 0.4μm +0.3μm/m.**
- **Thus, the multilateration method was introduced in order to reach high-precision measurements, prevent the influence of angle measurement error.**

Leica AT 960/930

1. **coordinate measurement accuracy:15μm +6μm/m**
2. **ADM: 10μm**
3. **IFM:0.4+0.3μm/m**

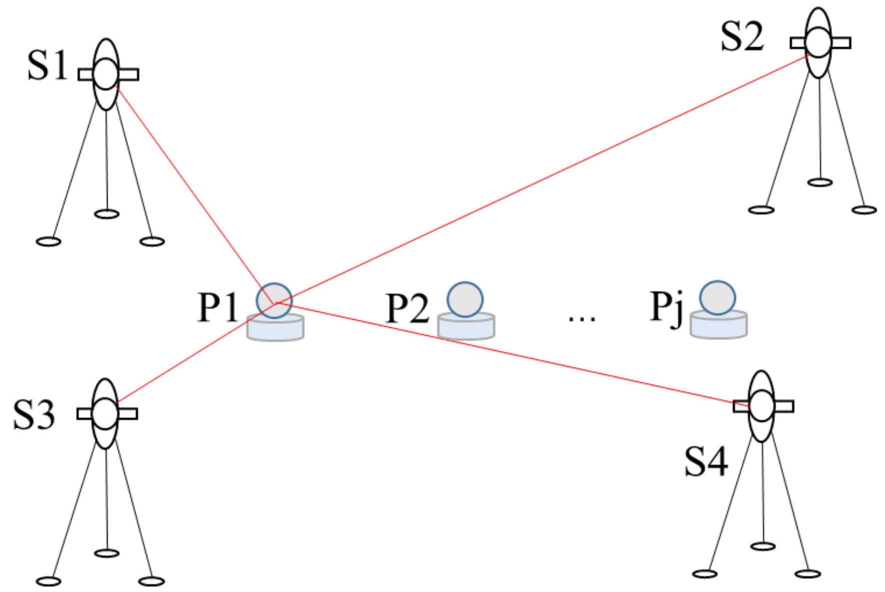


multilateration method

2. Multilateration Measurement method

- **The measurement principle of the multilateration measurement method mainly includes two parts: Self-calibration and Front measurement.**

1. **Self-calibration:** The system parameters, that is, the coordinates of the four stations, are solved by measuring enough points.
2. **Front intersection:** Calculate the coordinates of the under-test point. After the system parameters are determined, four stations are used to measure the distance to the under-test point at the same time, and then the coordinate of the point can be calculated based on the distance.



The principle multilateration measurement method

2. Multilateration Measurement method

Self-calibration:

we build a four-station laser trackers multilateration measurement system for magnet pre-alignment. Four stations were employed simultaneously to measure the distance to the target point. The error equation group can be expressed as:

$$\boldsymbol{D_{ij}} + \boldsymbol{v_{ij}} = \sqrt{(\boldsymbol{X_i} - \boldsymbol{x_j})^2 + (\boldsymbol{Y_i} - \boldsymbol{y_j})^2 + (\boldsymbol{Z_i} - \boldsymbol{z_j})^2}$$

The number of unknowns in error equation group is 3 (4+n), and the number of established equations is 4n. In order to make the system have a solution, the number of equations needs to be greater than or equal to the unknowns:

$$4n \geq 3(4 + \mathrm{n})$$

The above equation can be solved by using the principle of rank deficient free network adjustment.

$$V^T PV = \min$$

We can conclude that at least 4 instruments are needed to measure 8 common points simultaneously.

Front intersection :

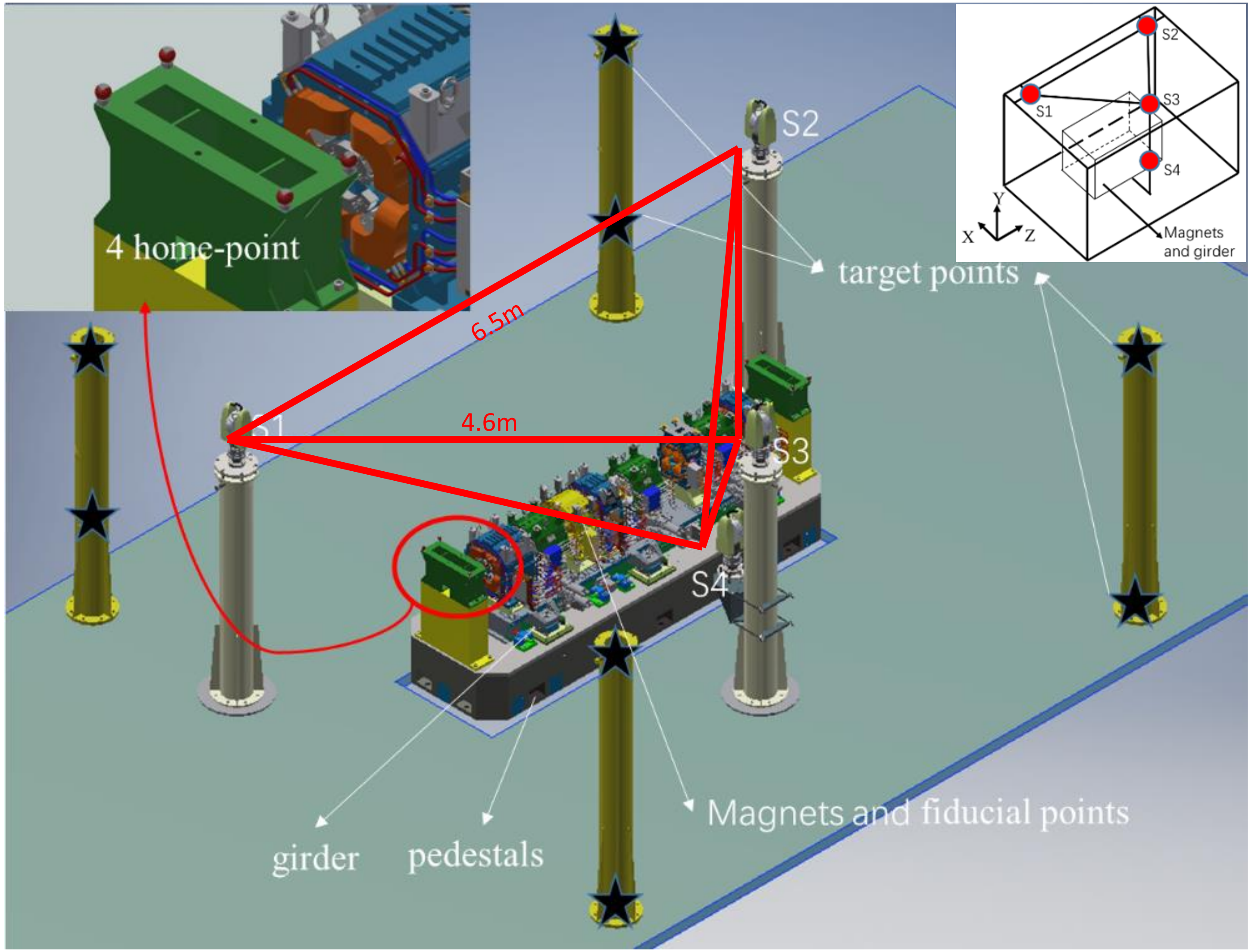
As the self-calibration process was completed, the coordinate of the four stations and the target points were obtained in one coordinate system. According to the principle of adjustment, the coordinates of the under-test point can be obtained.

2. Multilateration Measurement method

- The measurement accuracy of the system mainly depends on two parts, the system arrangement and the ranging accuracy.
- For each determined instrument, its ranging accuracy is determined, so the system arrangement largely determines the final accuracy of the system.
- We simulated about forty different arrangements.
- Find a arrangement that meets measurement accuracy.

The simulated point accuracy of the magnet fiducial points

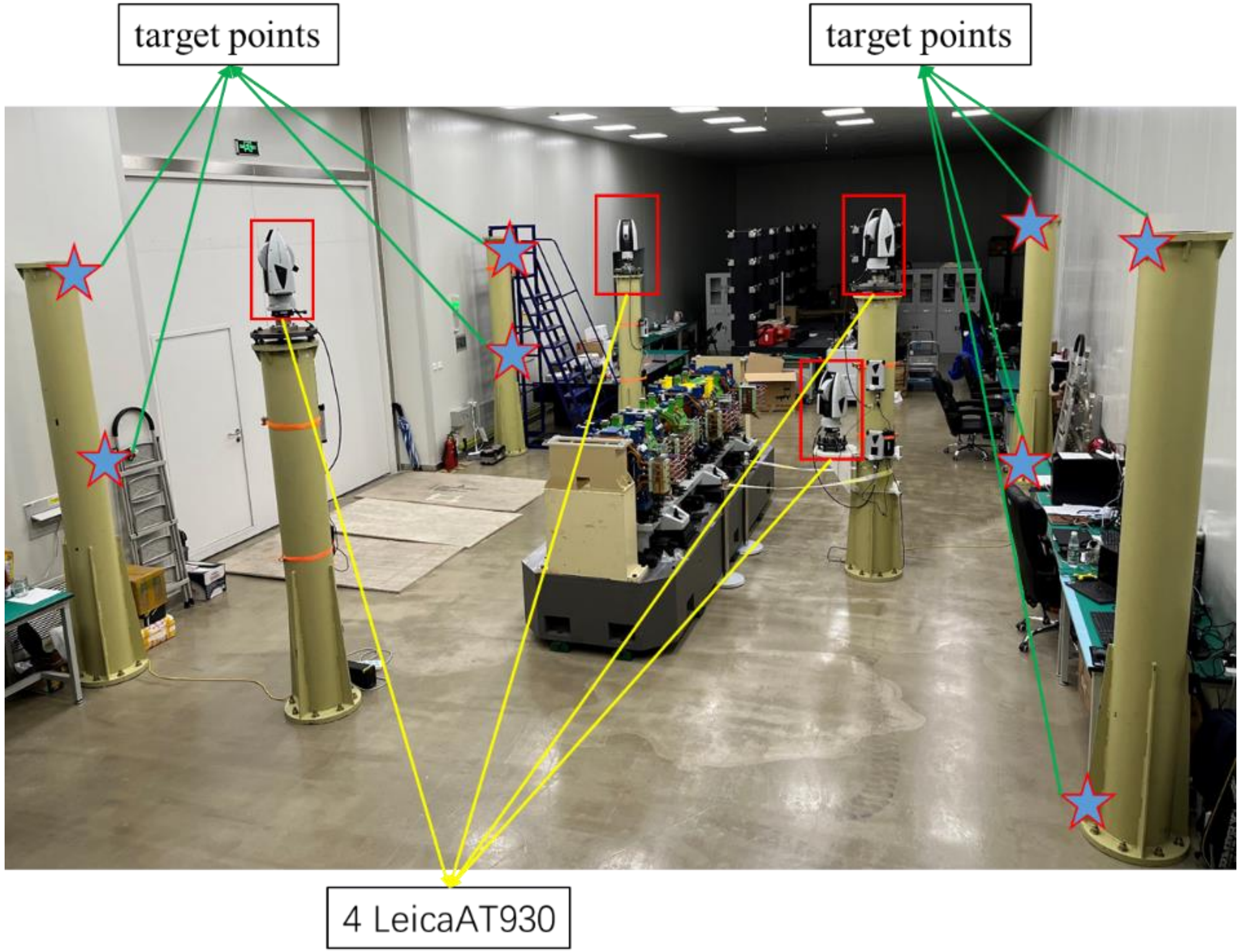
- Transverse X: 6μm
- Longitudinal Z: 4.5μm
- Vertical Y: 8μm



Measurement arrangement for pre-alignment of HEPS storage ring

2. Multilateration Measurement method

- According to simulation result, we use four leicaAT930 laser tracker build multiliteration measurement system (FLTMMS) .
- According to the previous pre-alignment plan, we set up 3 workstations in the laboratory.
- Two people are required per workstation.



FLTMMS for pre-alignment of HEPS storage ring

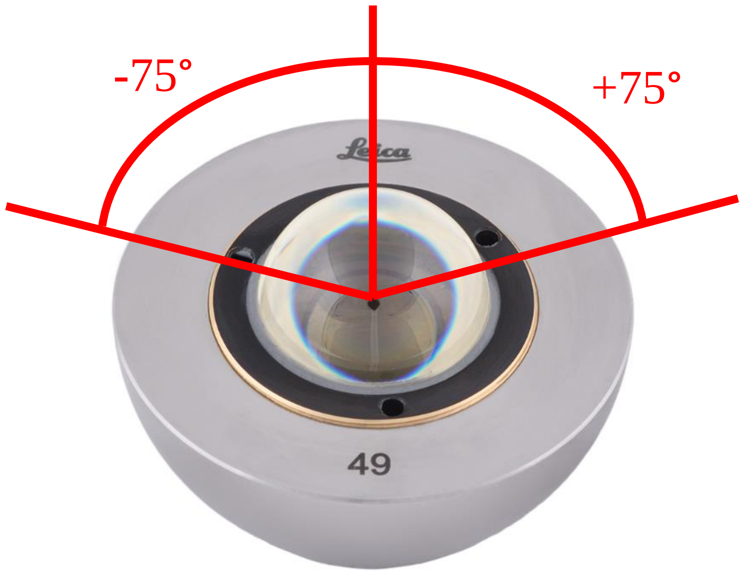
2. Multilateration Measurement method

- **Reflection target**

Leica Red Ring Reflection (RRR)

Acceptance angle of RRR is ±30°

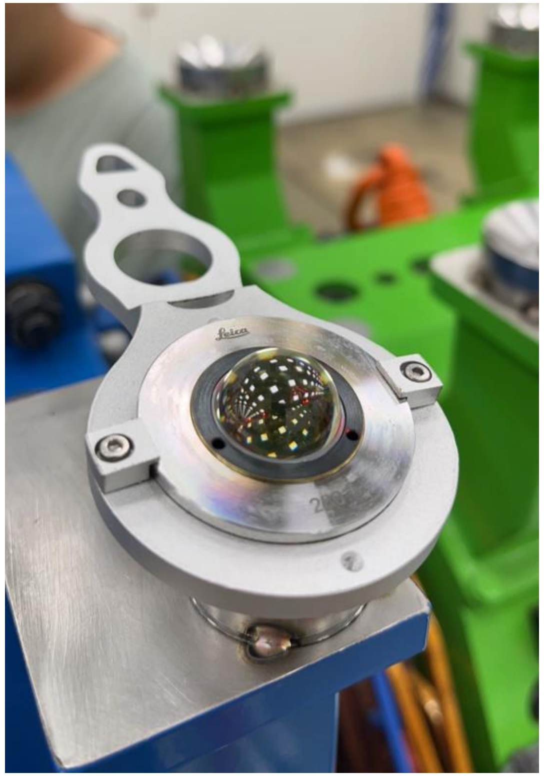
Self-calibration measurement



Super-Cat's Eye (SCE)

Vertical acceptance angle of SCE:
Vertical ±75°, horizontal 360°.

Front intersection



SCE handle

The experimental validation:

Absolute position measurement accuracy

Relative displacement measurement accuracy

2. Multilateration Measurement method

Absolute position measurement accuracy

Transverse X and Longitudinal Z directions are compared with Etalon Interferometer (EI) system. The direction of Vertical Y is compared to the 1m standard bar.

Etalon Interferometer (EI) system: 0.5μm/m

1m standard bar: 1000mm±2μm

Lengths and lengths deviation of FLTMMS and the Etalon Interferometer /mm

L1 (Z direction)	Times	1	2	3	4	5	Average value
	FLTMMS	4187.7559	4187.7537	4187.7548	4187.7596	4187.7618	4187.7572
	EI			4187.7566			
	Deviation	-0.0007	-0.0029	-0.0018	0.0030	0.0052	0.0006
L2 (X direction)	Times	1	2	3	4	5	Average value
	FLTMMS	558.9532	558.9522	558.9525	558.9511	558.9500	558.9518
	EI			558.9581			
	Deviation	-0.0049	-0.0059	-0.0057	-0.0071	-0.0082	-0.0063

Lengths and lengths deviation of FLTMMS and vertical standard bar /mm

Times	1	2	3	4	5	6	Average value
FLTMMS	999.9966	999.9885	999.9906	999.9931	999.9943	999.9943	999.9929
Deviation	-0.0034	-0.0115	-0.0094	-0.0069	-0.0057	-0.0057	-0.0071

- the deviations of the average value in the three directions are 6.3μm, 7.1μm, and 0.6μm, respectively.

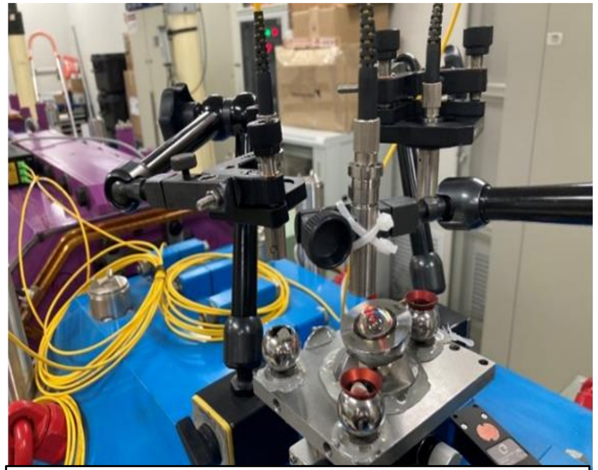
2. Multilateration Measurement method

Relative displacement measurement accuracy

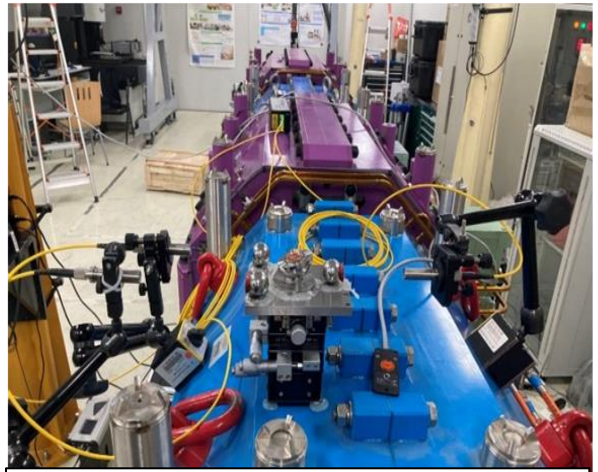
We compare the relative displacement measurement between FLTMMS and Attocube's IDS3005 Feedback Interferometer (FI: Feedback Interferometer)

IDS3005 measurement resolution：1pm

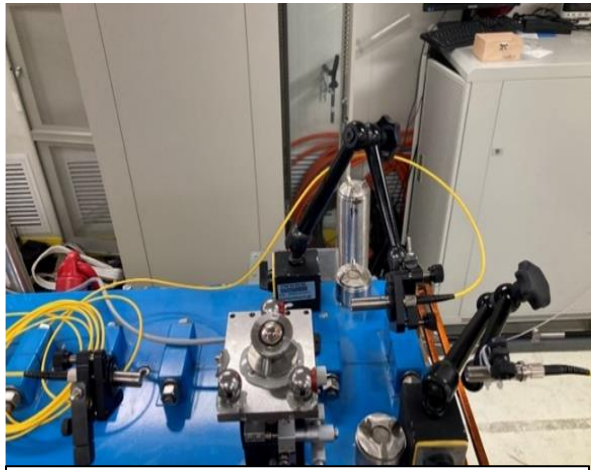
Relative displacement deviation/μm			
	X	Y	Z
Start	0	0	0
D01	-1.6	-0.3	0.8
D02	-0.2	0	2.5
D03	2.1	0.4	2.4
D04	-1.9	-0.8	1.3
D05	-1.1	-0.5	1.1
D06	0.5	0.8	1.9
D07	0.2	0.6	1.2
D08	1.2	0.3	2.3
MAX	**2.1**	**0.8**	**2.5**
MIN	**-1.9**	**-0.8**	**0.8**
STD	1. 3	0. 5	1. 8



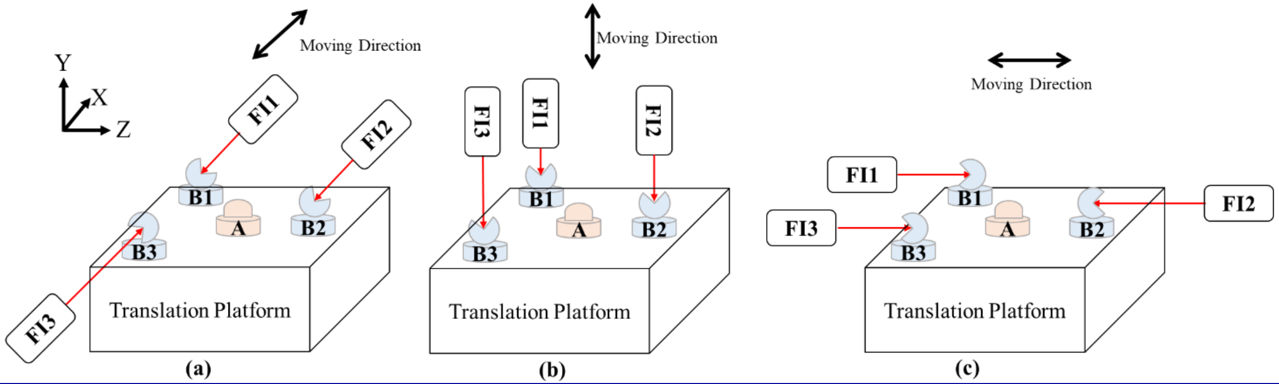
Vertical Y directions



Transverse X directions

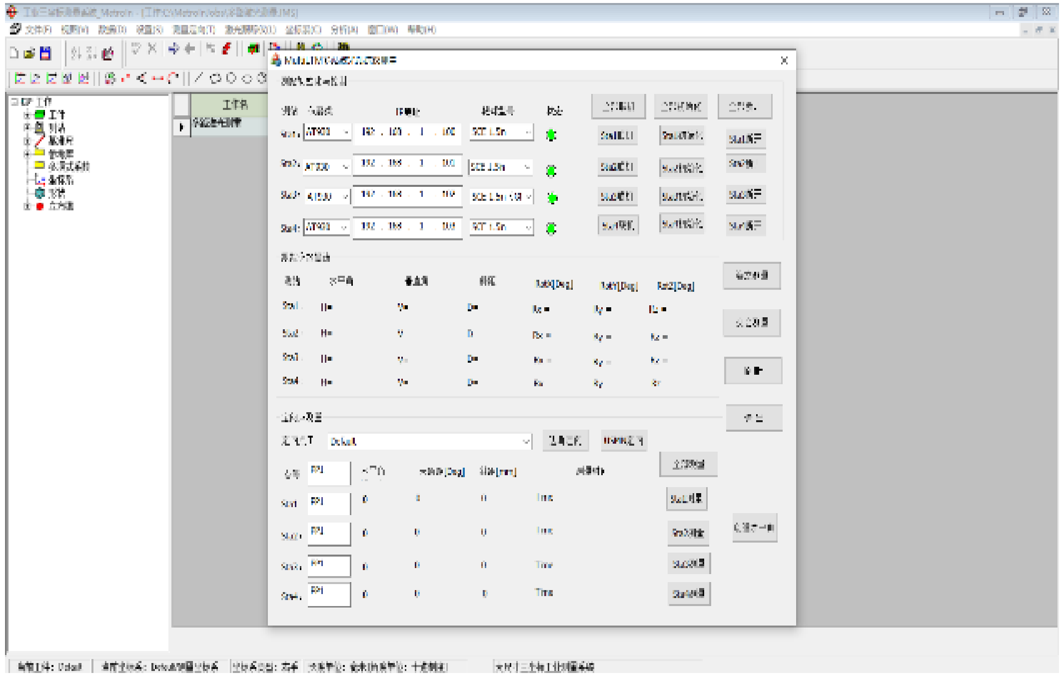


Longitudinal Z directions



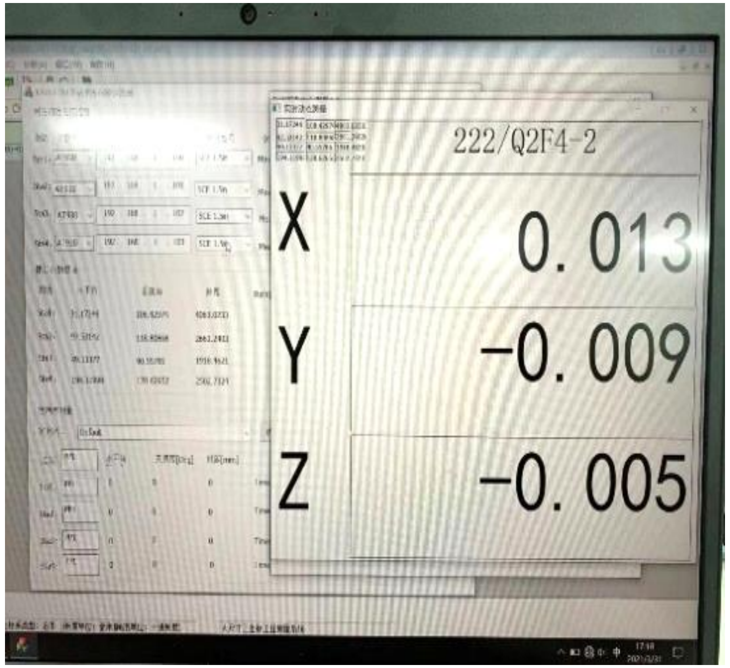
2. Multilateration Measurement method

- **Measurement software development**
- **In order to apply Multilateration Measurement Method to the pre-alignment.**
- **Functions: instrument connection, Self-calibration, Front intersection, dynamic display coordinates, automatic aiming point, stable measurement and so on 。**



Main measurement interface

instrument connection



dynamic display coordinates

3. Pre-alignment specific steps of HEPS Storage Ring

- There are three main steps in pre-alignment:

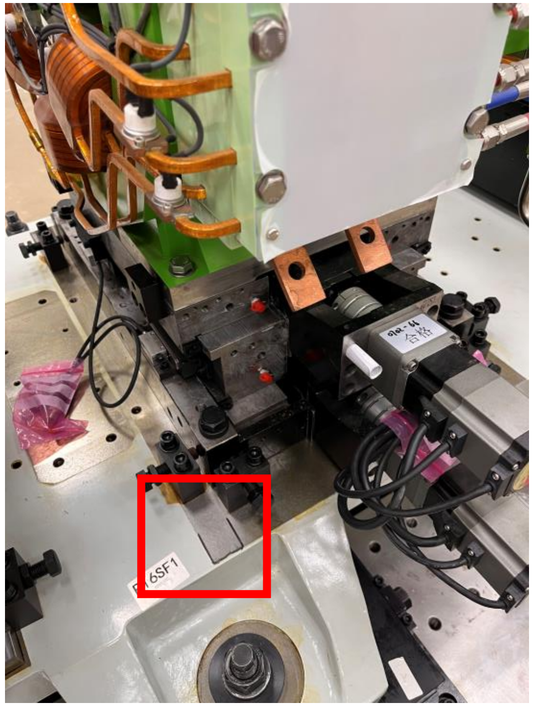
Girder fiducialization → **Magnets alignment and locking** → **Final measurement and replacement of the girder**

- **Girder fiducialization**

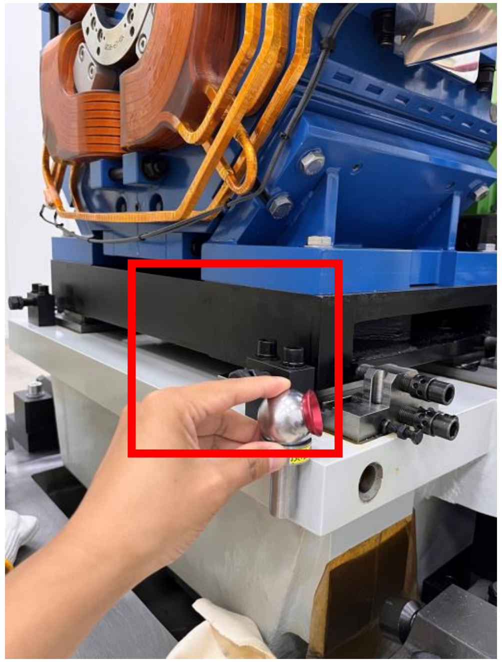
  -Single AT930 laser tracker

  -Measure the corresponding position

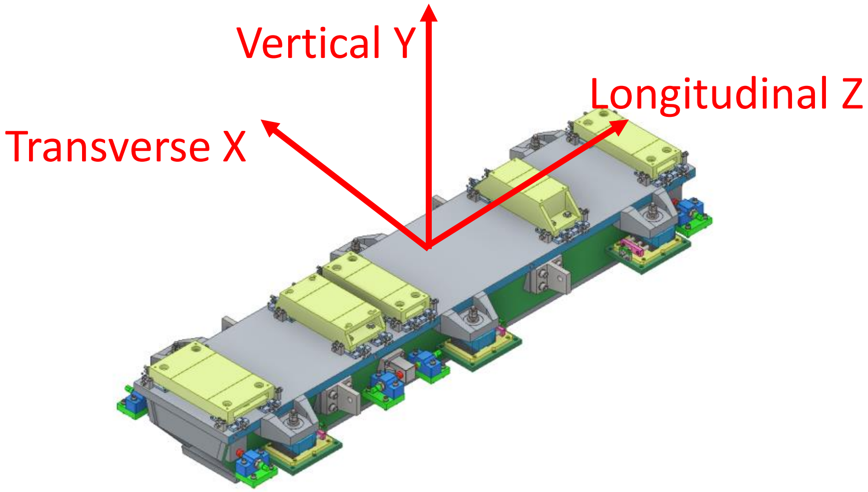
  -Establish girder frame.



Girder top plane



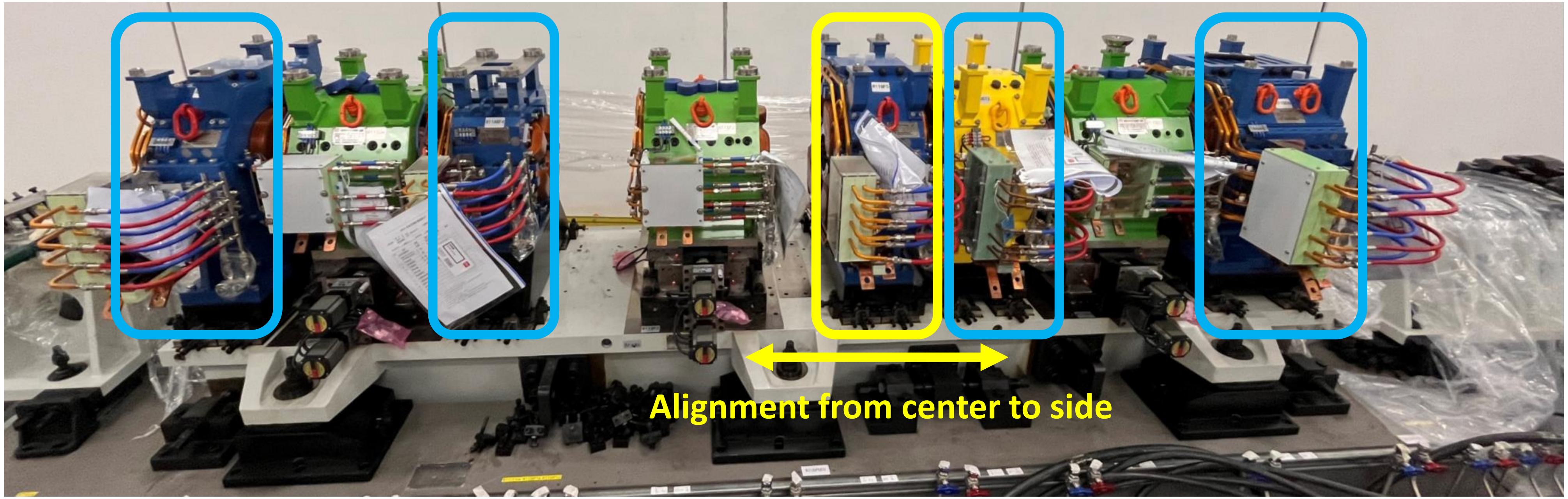
Girder side



Girder Frame

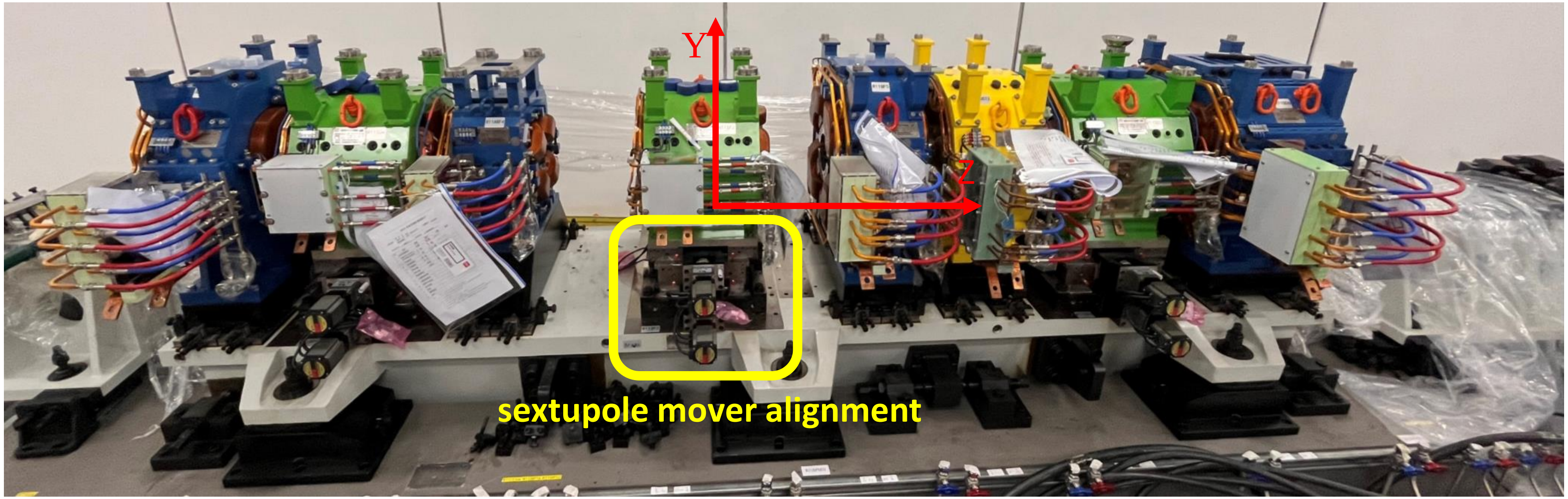
- **Magnets alignment and locking**

  - **Main magnet：** Chose the magnet in the middle of girder, using single Leica AT930.
  - **Quadrupole and octupole magnet：** alignment relative to main magnet. Using mutilateration method. Adjust the magnet to theory position, then lock the magnet. Before locking, lose all the transverse and longitudinal adjust machine.



- **Magnets alignment and locking**

  - **Sextupole magnet and mover alignment：** There are three sextupole on each MP girder. There is a mover between sextupol and girder. Mover can automatic move for transverse and vertical direction. So we need alignment the mover first. Parallel to relative axis. Mover transverse can move from -20mm to +20mm,vertical can move from -1mm to +1mm, when mover move in this range the Z coordinate change within 10 micrometer.

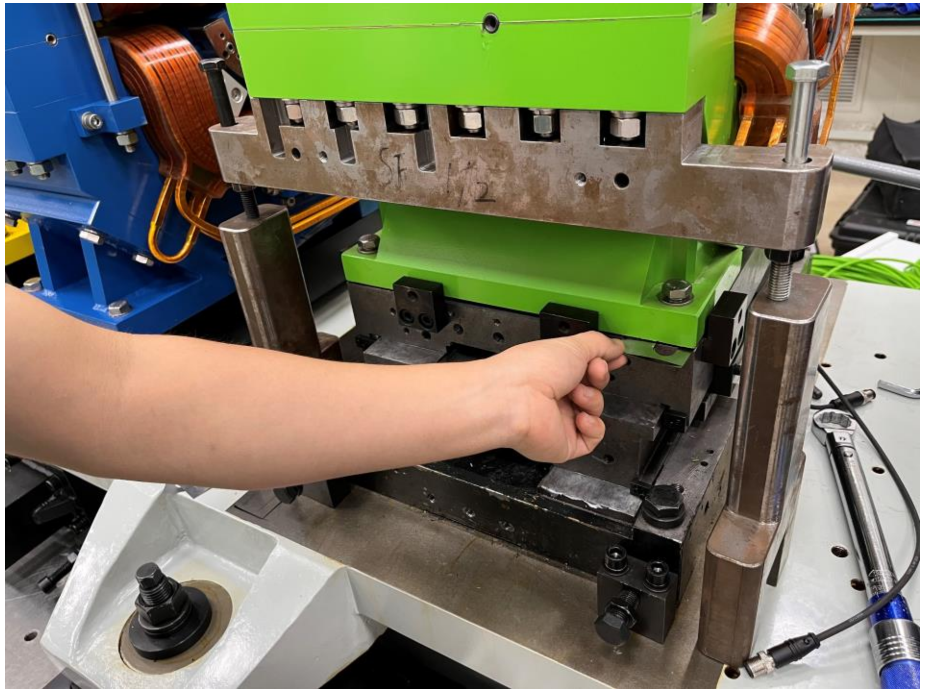


3. Pre-alignment specific steps of HEPS Storage Ring

- **Magnets alignment and locking**

  - **There is no Y-direction adjustment mechanism between the sixth-magnet and the mover, and the functions of the adjustment mechanism are adjusted horizontally and vertically.**
  - **Use shims to place the height in the Y direction to the theoretical position.**
  - **A lifting tooling is specially designed, lift the magnet and insert shims, lock.**

Choose appropriate thickness shims

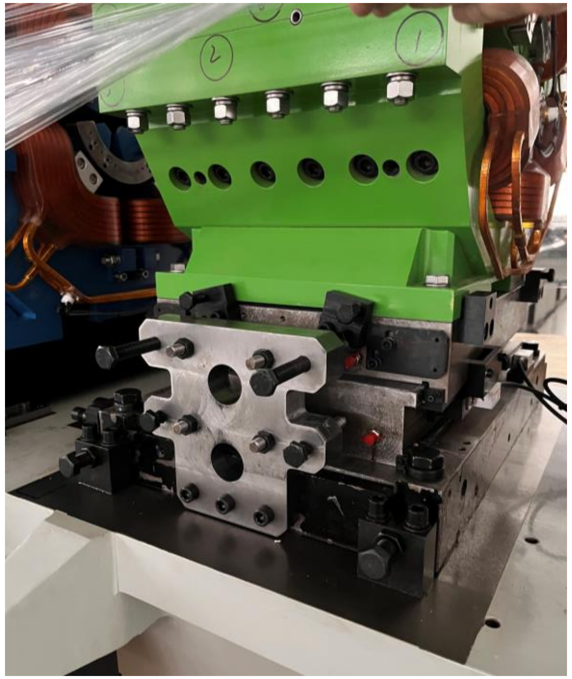


Lift the magnet and insert shims

3. Pre-alignment specific steps of HEPS Storage Ring

- **Final measurement and replacement of the girder**

  - After all magnets are aligned, use the multilateration method to **measure all magnets on the girder as the final pre-alignment result**.
  - Because the girder needs to be transported to the tunnel, in order to prevent the mover from moving during transportation, it is also necessary to **use a fixing plate to fix the mover**.
  - Finally, use a forklift to replace the girder.



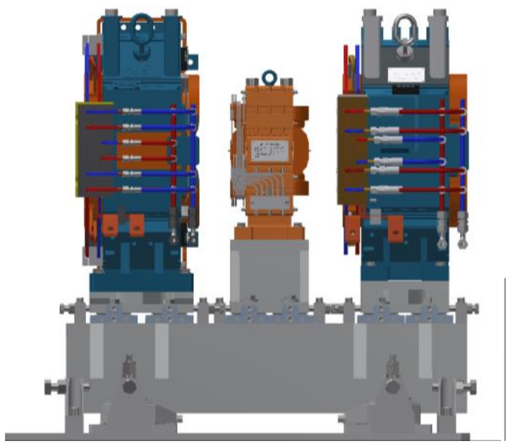
Install the fixing plate

replacing the girder

4. Pre-alignment efficiency and results

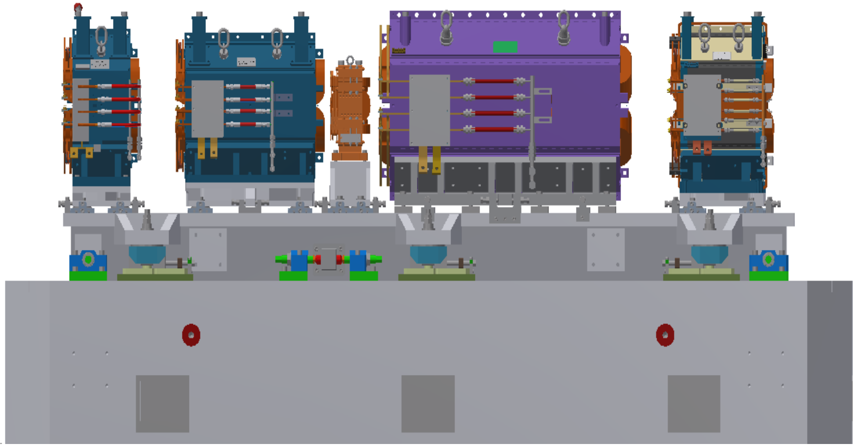
- **Starts: October 1, 2022.**
- **Finish: November 31, 2023**
- **Total girder: 288**

- **Take measures to improve efficiency**
  - ➢ **Create a pre-alignment standard Excel table**
  - ➢ **Optimize and reduce the measurement steps**
  - ➢ **Improve the proficiency of magnet adjustment**



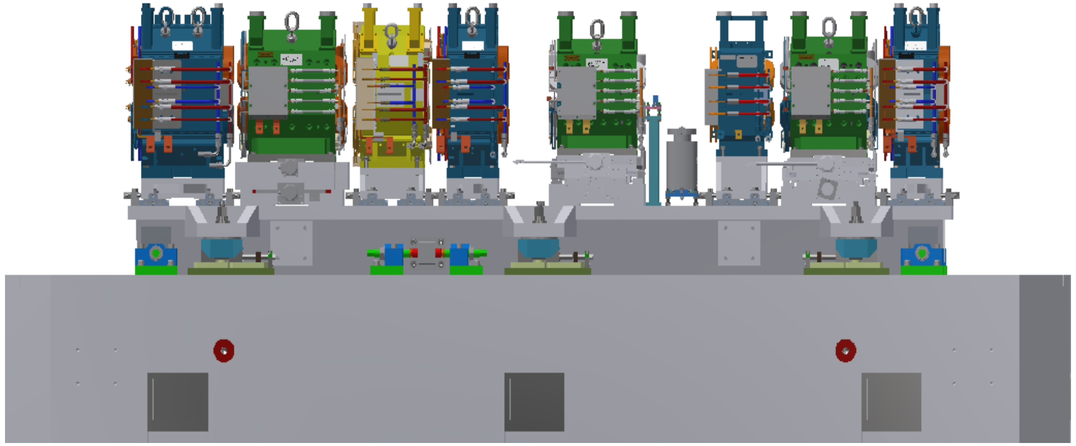
DQ

1 day
per girder



FD

2 day
per girder



MP

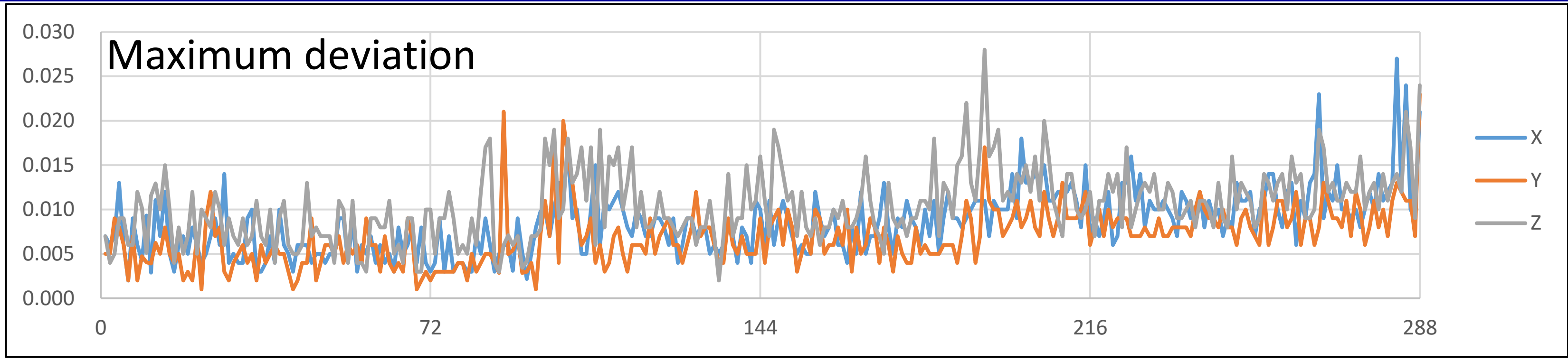
3 day
per girder

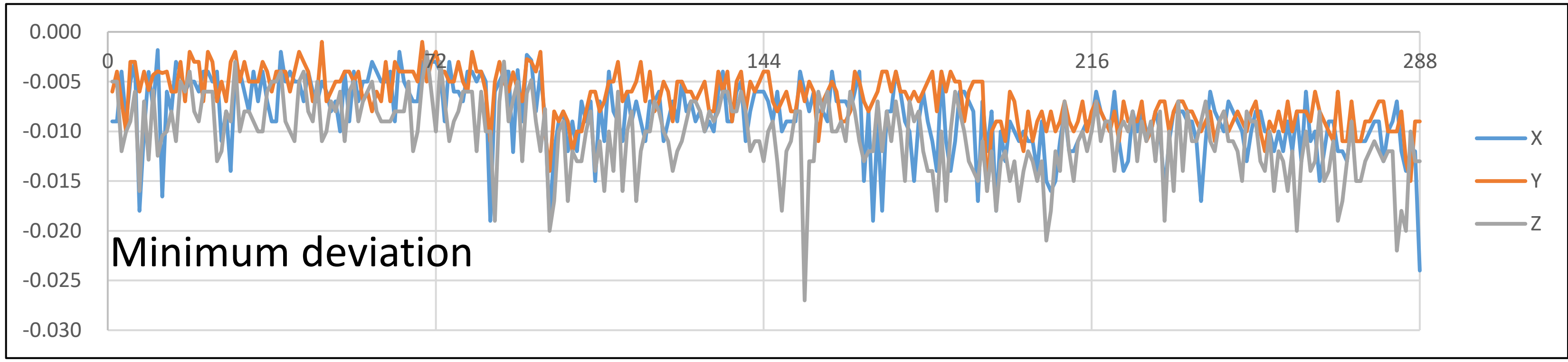
- **Three workstations were built to work in batches.**
- **We can align one cell (2 DQ girder, 2 FD girder and 2 MP girder) in five working days.**

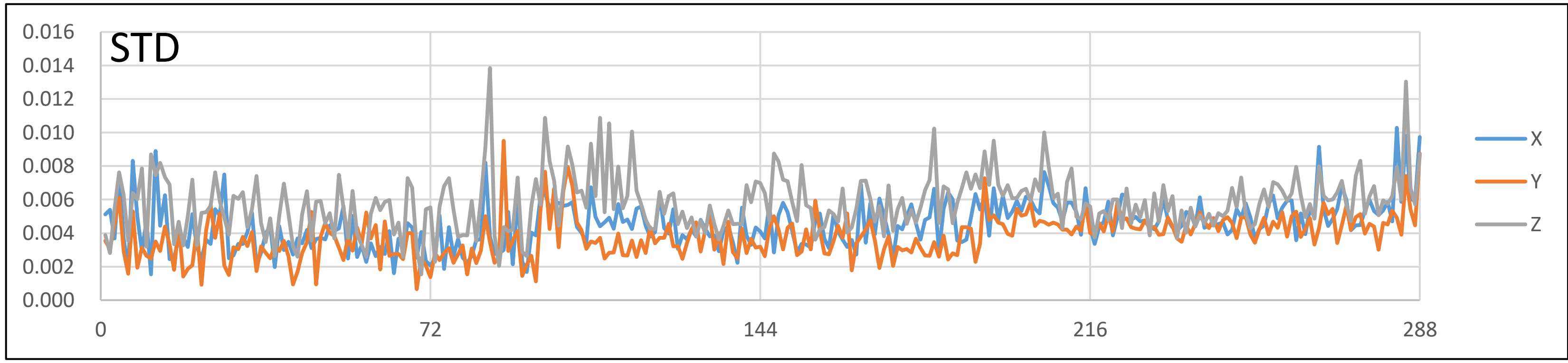
4. Pre-alignment efficiency and results

- **Measurement in the laboratory，288 girders**
- **Meet pre-alignment requirements**

Deviation of 288 girders			
	X	Y	Z
MAX	0.027	0.023	0.028
MIN	-0.024	-0.016	-0.027
STD	**0.010**	**0.010**	**0.014**

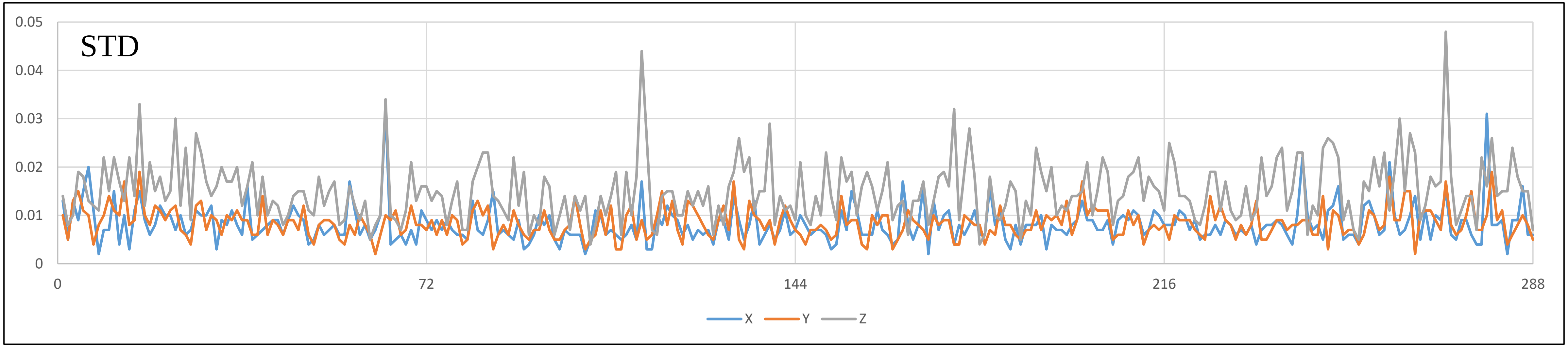






4. Pre-alignment efficiency and results

- **Measurement after transport to the tunnel**
  -There are two girders with RMS in the X direction exceeding 30 μm
  -31μm (R11FD2) and 32μm (R47FD1) respectively.



- **There is a magnet inside these two girders that has translation in the X direction. Since pre-alignment in the tunnel is particularly difficult and translation is very small, we do not deal with these two girders.**

Maximum RMS of 288 girders			
	X	Y	Z
RMS	0.032	0.019	0.048

- **Pre-alignment finish on November 31, 2023, 2024.7.23, Accelerator startup**

Summary

- ◆The measurement method can achieve an absolute position measurement accuracy of 10μm, meeting the pre-alignment requirements;
- ◆The measurement method has a relative displacement measurement accuracy of 3μm, which meets the Mover adjustment requirements;
- ◆The pre-alignment process and the adjustment and locking method are reliable and effective, and can achieve high-precision and high-efficiency pre-alignment of the girder.

Thank you!


HEPS储存环单元预安装准直
2022年7月13日——2023年7月12日
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