中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES


# Mechanics and alignment of accelerator

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# Content

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# Accelerator Mechanical Engineering

The task of accelerator mechanical engineering is to complete the general layout design, mechanical system design, component installation and alignment of accelerator components, based on the lattice design and requirements of components, providing **stable** and **accurate** reference orbits for the operation of electron beams.

**Mechanical Stability**：Vibrations、Long term settlements & Thermal stability

**Accuracy**：Alignment

# Accelerator Mechanical Engineering

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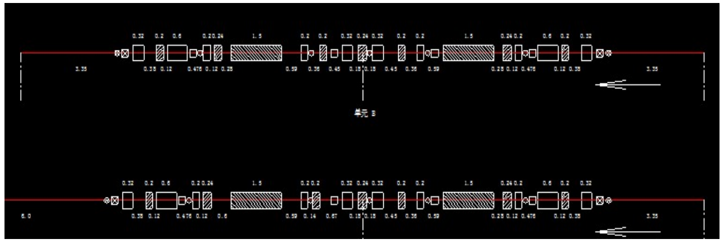
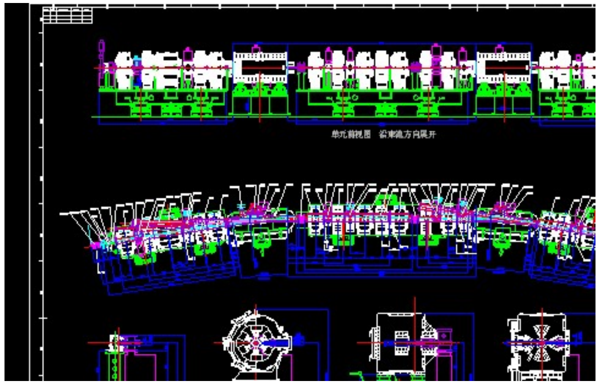
Lattice

Input



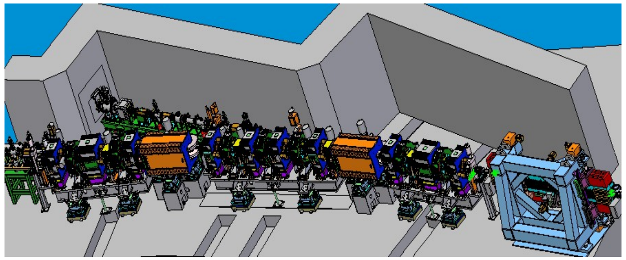


Component engineering design

Process

Manufacture and installation

Result



General layout design

# Beam Stability Criteria

**Photon**

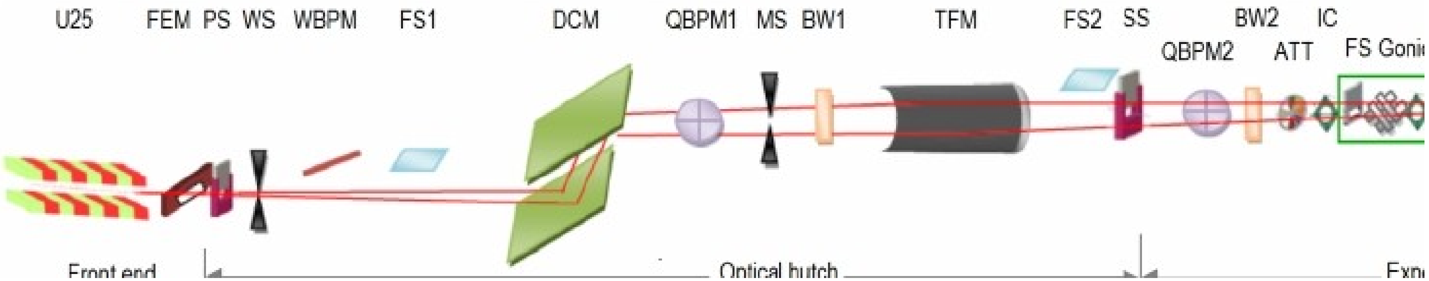
Photon beam intensity fluctuation $\Delta I/I$: ~0.1%

Photon energy resolution $\Delta E/E$: ~$10^{-4}$

**Electron**

Position stability $\Delta\sigma_x/\sigma_x$ and $\Delta\sigma_y/\sigma_y$: 10% ( **beam size**)

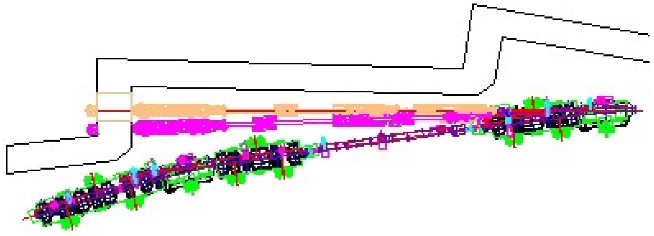
Angular stability $\Delta\sigma'_x/\sigma'_x$ and $\Delta\sigma'_y/\sigma'_y$ : 10%




Light source, beamline and experimental station

# Beam Sizes of Source Points

ID beamlines
Share the front-end



BM beamlines
Separate front-ends

| Source Point | $\sigma_x$(μm) | $\sigma_x'$(μrad) | $\sigma_y$(μm) | $\sigma_y'$(μrad) |
|---|---|---|---|---|
| Standard Straight (6.5m) | 158 | 33 | 9.9 | 3.95 |
| Long Straight (12.0m) | 247 | 20 | 15 | 2.55 |
| 1°@upstream of SS | 70 | 114 | 22 | 1.97 |
| 3.1°@upstream of SS | 53 | 94 | 22 | 1.97 |
| 1°@upstream of LS | 77 | 116 | 23 | 1.79 |
| 3.1°@upstream of LS | 56 | 96 | 23 | 1.79 |

Electron beam size and angle in SSRF

# Orbit Stability Requirement

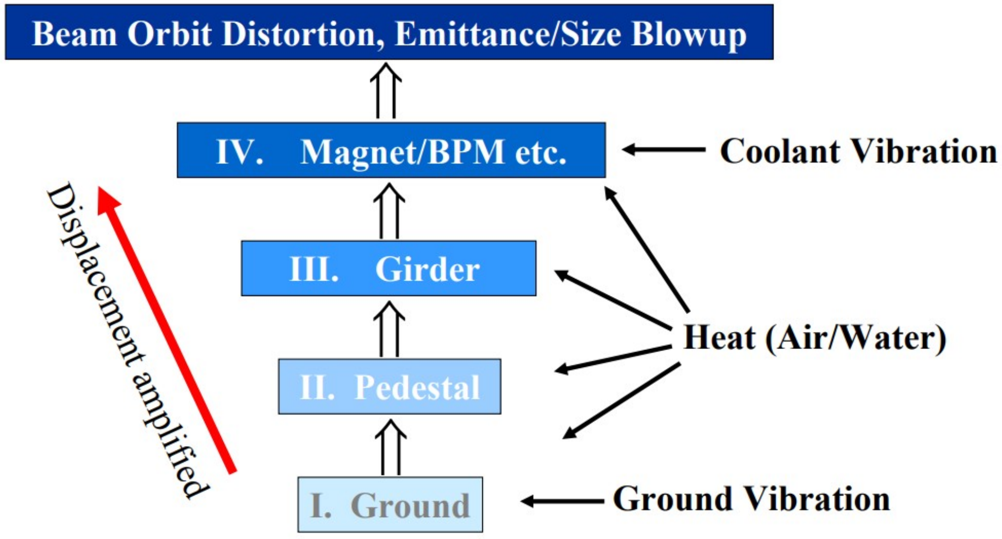
| Source Point | $\sigma_x$(μm) | $\sigma_x'$(μm) | $\sigma_y$(μm) | $\sigma_y'$(μm) |
|---|---|---|---|---|
| Short Straight (6.5m) | <16 μm | <3 μrad | <1 μm | <0.4 μrad |
| Long Straight (12.0m) | <25 μm | <2 μrad | <1.5 μm | <0.3 μrad |
| 1°@upstream of SS | <7 μm | <11 μrad | <2 μm | <0.2 μrad |
| 3.1°@upstream of SS | <5 μm | <9 μrad | <2 μm | <0.2 μrad |
| 1°@upstream of LS | <8 μm | <12 μrad | <2 μm | <0.18 μrad |
| 3.1°@upstream of LS | <6 μm | <10 μrad | <2 μm | <0.18 μrad |

Orbit stability goal in SSRF:

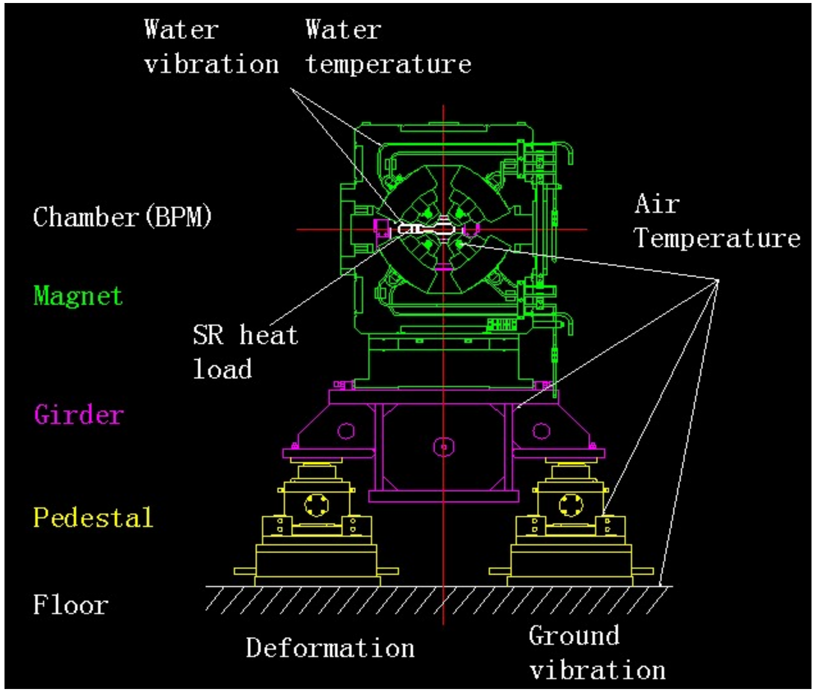
Horizontal orbit stability < 5 μm

Vertical orbit stability <1 μm

# Mechanical Effect on Beam Orbit and Size




MEDSI 2004, JR Chen



# Mechanical Stability Requirements in SSRF

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## Long term

Slab deformation at ring tunnel and experimental hall

$\Delta z$ <100μm/10m/year
$\Delta z$ <10μm/10m/day
$\Delta z$ <1μm/10m/hour

## Medium term

Air temperature stability (12hours)

Ring Tunnel: T= ~26 $^0$C ; $\Delta T$ <±0.1$^0$C
Experimental: T=22 ~26 $^0$C ±2$^0$C

Cooling water temperature stability (12hours)

Ring tunnel: T= ~ 30$^0$C ±0.1$^0$
Magnet PS: T= ~ 30$^0$C ±1$^0$C

# Mechanical Stability Requirements in SSRF

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## Short term

Slab vibration amplitude (0.2 ~100Hz)

Original: Vertical: $\Delta z < 1\mu m$ (peak to peak )

Horizontal: $\Delta x < 2\mu m$ (peak to peak)

Modified to integrated rms displacement above 1Hz:

Vertical: $\Delta z < 0.15\mu m$ (quiet)

$\Delta z < 0.3\mu m$ (noisy)

Horizontal: $\Delta x < 0.3\mu m$ (quiet)

$\Delta x < 0.6\mu m$ (noisy)

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1.Overview

2.Mechanical Stability

3.Alignment

4.Monitoring deformation

4.Summary

# Ground Vibration

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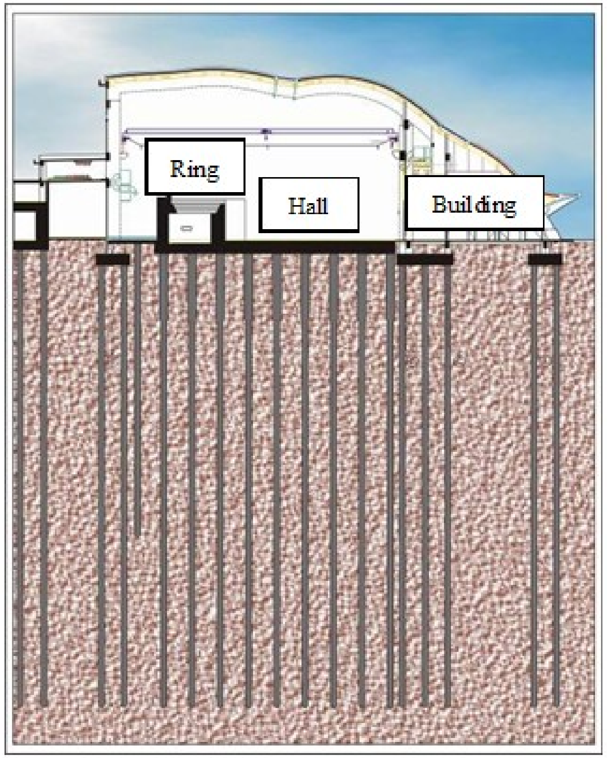
The ground vibrations could be divided into two classes : natural site vibration and culturally induced vibration

| Site location | Average rms (nm) | $\sigma$ (nm) | Day rms (nm) | Night rms (nm) |
|---|---|---|---|---|
| ALBA | 18.8 | 9.5 | 42.0 | 9.1 |
| APS | 10.7 | 1.0 | 11.0 | 9.8 |
| Asse | 0.6 | 0.1 | 0.7 | 0.5 |
| BESSY | 75.0 | 28.1 | 140.7 | 53.1 |
| BNL | 89.6 | 30.2 | 135.3 | 29.1 |
| CERN LHC | 1.9 | 0.8 | 2.8 | 0.9 |
| DESY HERA | 53.3 | 18.9 | 77.0 | 34.8 |
| DESY XFEL O | 29.1 | 11.9 | 48.4 | 19.5 |
| DESY XFEL S | 41.1 | 16.6 | 70.0 | 35.1 |
| DESY, Zeuthen | 64.4 | 40.4 | 75.6 | 88.5 |
| Ellerhoop | 18.2 | 8.4 | 35.9 | 9.3 |
| ESRF | 74.0 | 34.9 | 137.2 | 40.2 |
| FNAL | 3.0 | 0.9 | 4.0 | 2.2 |
| IHEP | 8.5 | 0.5 | 9.0 | 8.1 |
| KEK | 80.5 | 36.0 | 125.1 | 38.0 |
| LAPP | 3.6 | 1.6 | 7.0 | 1.9 |

# Ground Vibration




- Slab for ring tunnel and experimental hall is separated with building
- Bored piles with base grouting

  Number: 2100

  Diameter: 0.6m ( 0.9m for top 7m )

  Length: 48m ( To silty sand layer)
- Slab Thickness

  1.35m ( experimental hall )

  1.05m ( ring tunnel )

# Ground Vibration

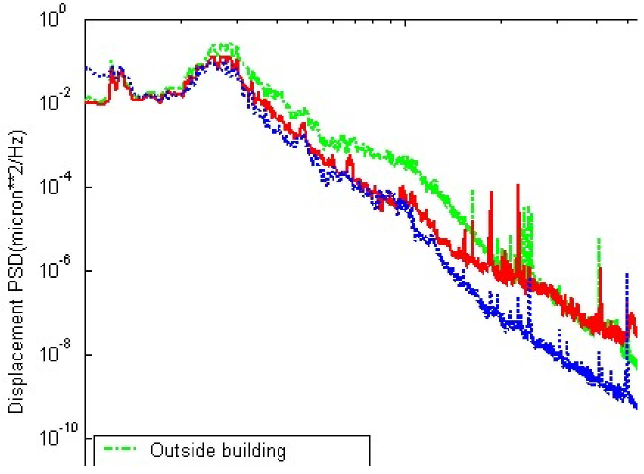
Slab vibration:

Vertical rms value

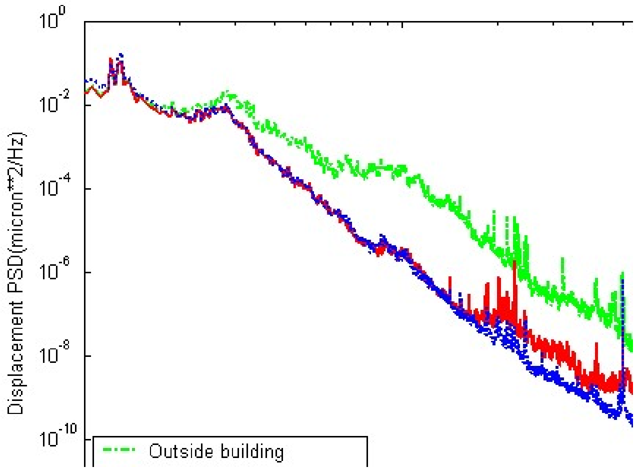
~0.15 μm (quiet time)

~0.25 μm (noisy time)

RMS value decrease about 50% in vertical direction




PSD in Horizontal Direction




PSD in Vertical Direction

# Isolation Vibration

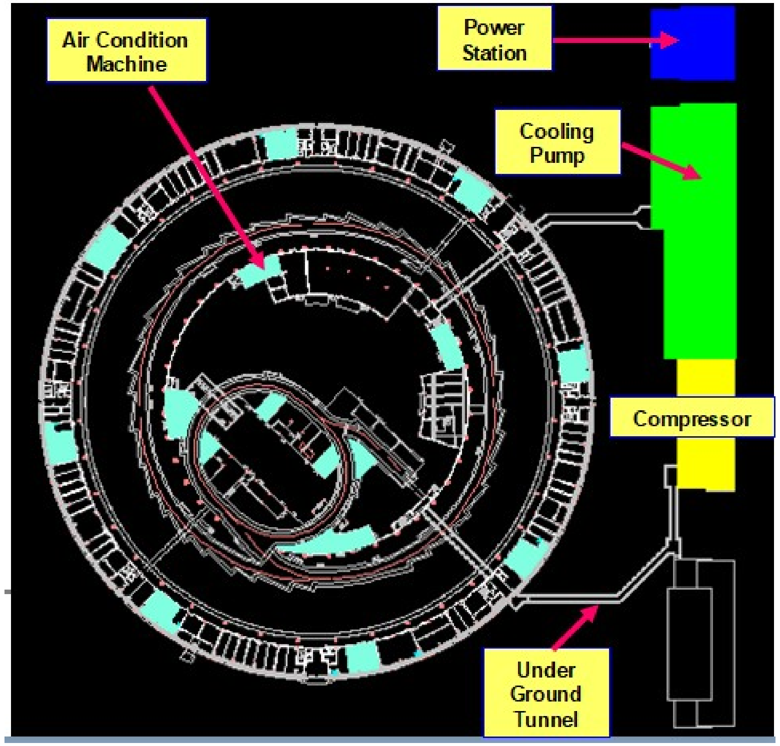
Keep pumps and compressors far from the storage ring

Utility facilities are arranged outside the main building

Main cooling cycles are set in the alleyway in the main building

Water flow rate is limited to 2m/s in magnet and absorber

Air condition machines with damping are located inside the main building.



# Isolation Vibration

Branches from the main cooling loop connect the machine in each cell

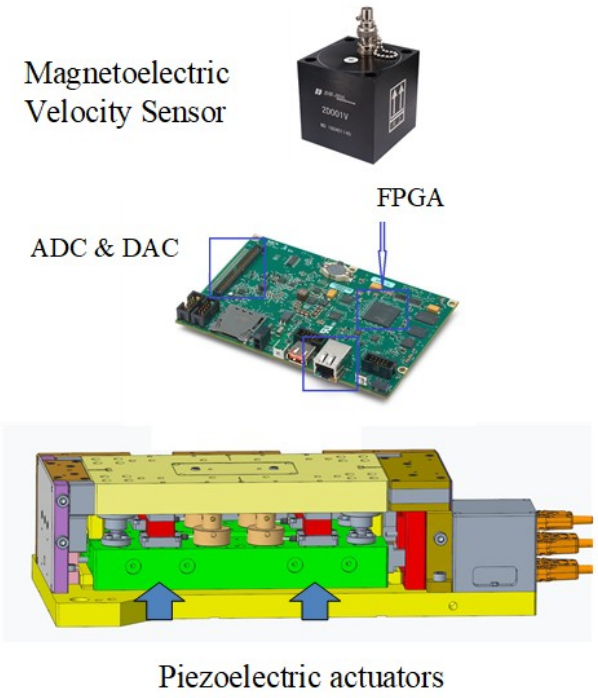
Soft pipe mechanical isolate the main pipe with accelerator components

Keep large curve in cooling path for components

Air flows to tunnel uniformly and not blows to components directly

Temperature sensors are set near high precision BPM


# Active Vibration




**Working principle of active vibration**

### 1、Vibration Sensing

High-sensitivity sensors detect vibration signals in real time and convert mechanical vibrations into electrical signals.

### 2、Signal Processing & Control

A control algorithm analyzes vibration characteristics and generates an inverse-phase control signal with matched amplitude to counteract disturbances.

### 3、Piezoelectric Ceramic Actuator

The control signal drives piezoelectric actuators to rapidly deform (microsecond-level response), generating opposing forces to cancel vibrations. The inverse piezoelectric effect enables precise conversion of electrical energy into mechanical motion.

# Active Vibration

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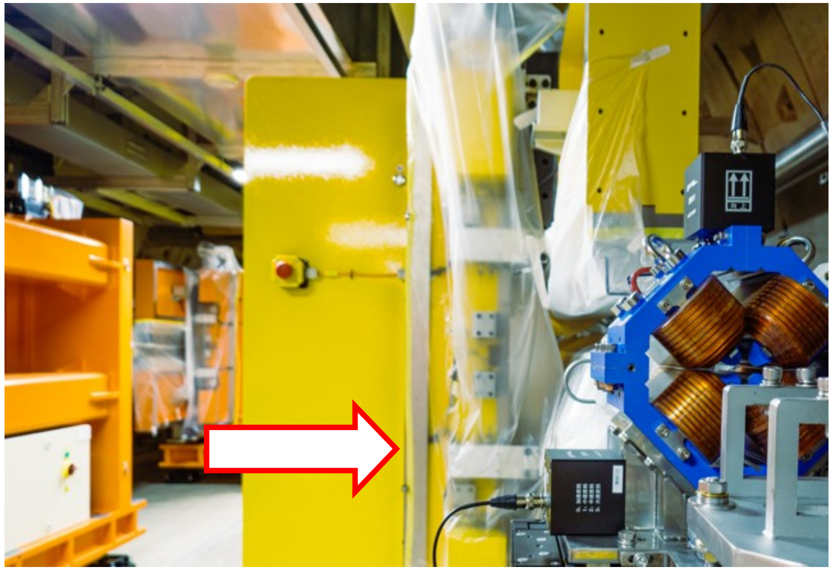
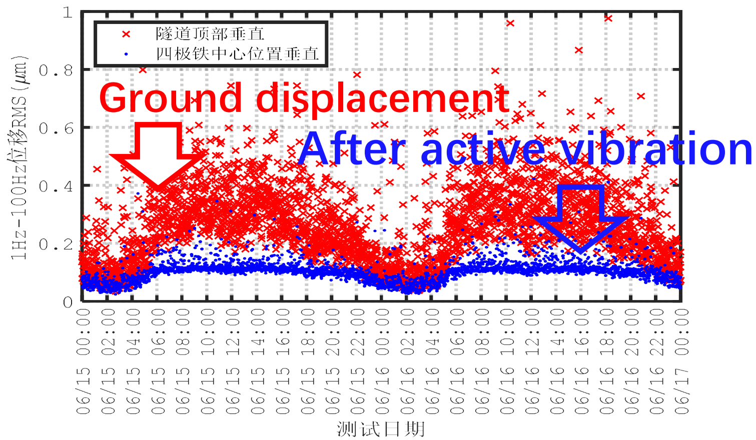


**Active vibration for quadrupole in SHINE**




**Test result in vertical direction of active vibration**

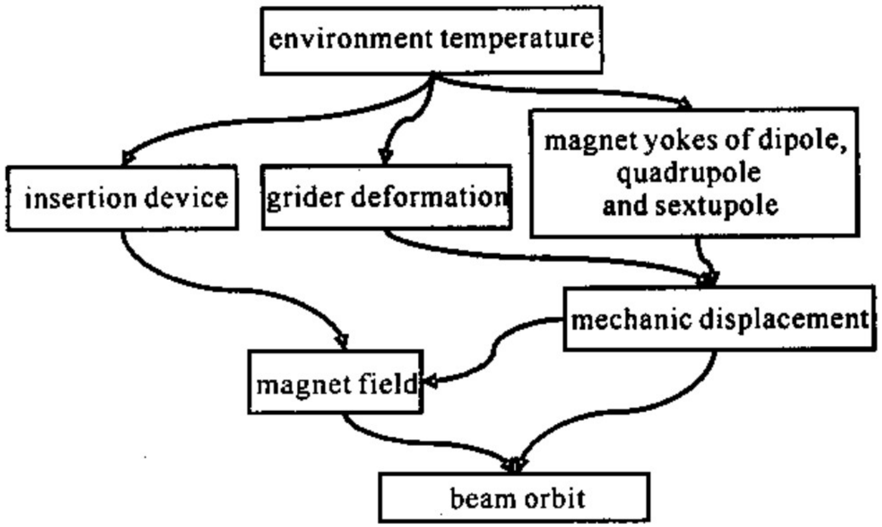
# Thermal stability

Air Temperature Fluctuation

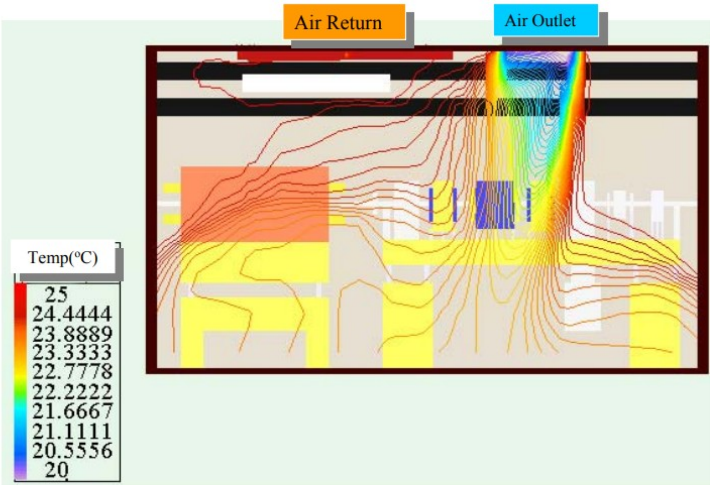
Water Temperature Fluctuation

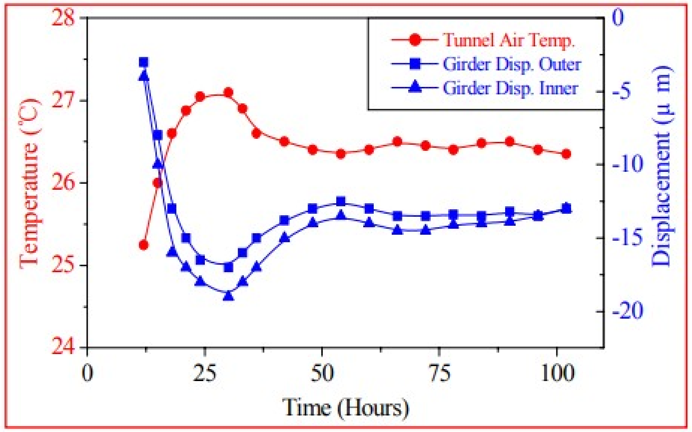
Synchrotron Light Radiation

Power Supply and Electrical Heating



# Air Temperature



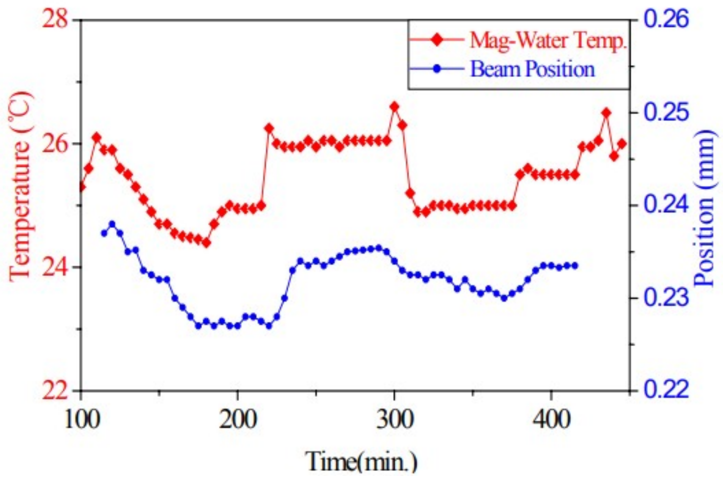




Sensitivity to air temperature: ~10 μm/ ℃

Induced beam orbit drift: 10-30 μm/ ℃

Air temperature : < ±0.1℃

# Water Temperature_Magnet




Temperature fluctuations of magnet cooling water

Magnet deformed ~10μm/℃

Induced beam orbit drift: 5-50 μm / ℃

Cooling water temperature: ~ ±0.1℃

# Temperature Fluctuation

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Sensitivity of the fluctuations in beam orbit, beam size and the displacements of main components to the fluctuations in the air and water temperatures

| Heat source | Current Temp. Fluctuation | Amplification factor | | Amplification factor (component displacement) | | |
|---|---|---|---|---|---|---|
| | | Beam orbit | Beam size | Girder | Magnet | BPM |
| Air Temp. | < ±0.1℃ | 20-100μm/℃ | - | ~10 μm/℃ (ver.) | - | - |
| Water Temp. (magnet) | < ±0.1℃ | 5-50 μm/℃ | - | - | ~10μm/℃ | - |
| Water Temp. (rf) | < ±0.02℃ | - | ~20 μm/℃ (hor.) | - | - | - |
| Water Temp. (vac-outlet) | ~ ±0.5℃ | 10-30μm/℃ | - | ~0.3μm/℃ | - | ~1 μm/℃ |

# Mechanical System

Support, Adjustment,Transportation, Installation

Pre_assembly and transportation

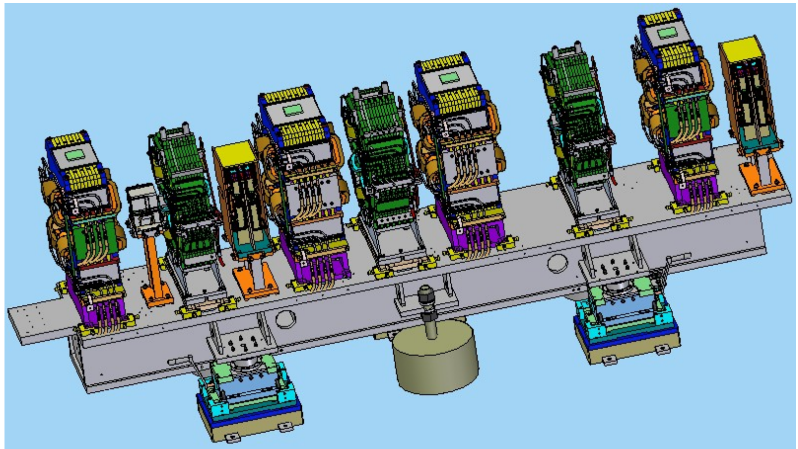
Easy installation in the SR tunnel

Precision alignment of the magnets

High mechanical stability (vibration and thermal)

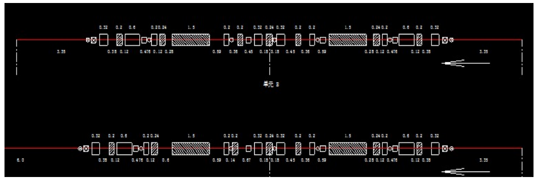
Increase natural frequency

Meet budget and schedule

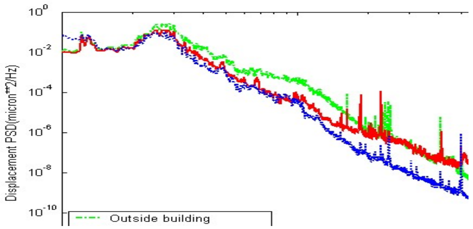


# Design Process

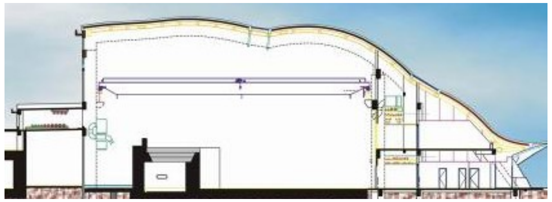
**Environment**



Lattice




Ambient motion

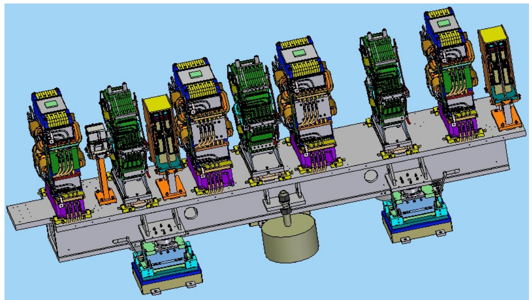


Bldg

Requirements/Specs.

- Alignment
- Stability
- Transportation
- Installation

Design optimization should consider trade-off between performance, environmental conditions , requirements and engineering feasibility.

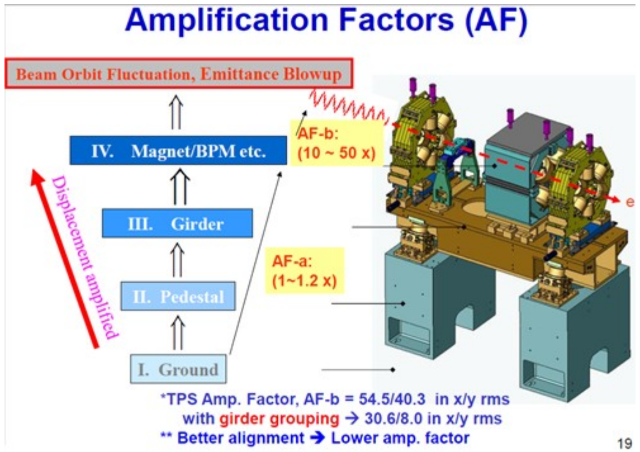


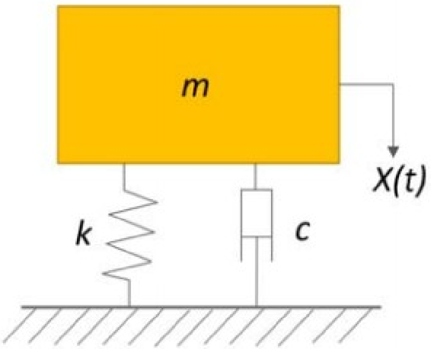
Evaluate Performance

Vacuum pump layout causes adjustment of magnet spacing

# Natural frequency

The energy of ground vibration is mainly concentrated in the low frequency range, and as the frequency increases, the energy rapidly decreases. Therefore, if the magnet girder has a high natural frequency, it will be very effective for controlling the amplitude of the magnet. The natural frequency of the magnet girder should be increased as much as possible to obtain better beam stability



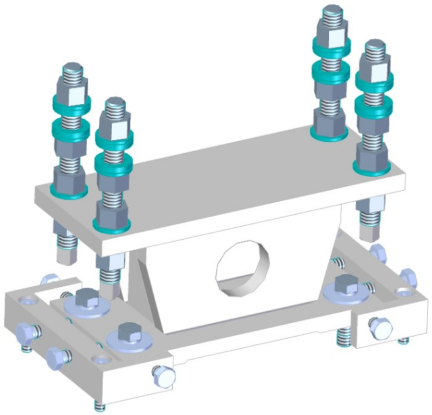




$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

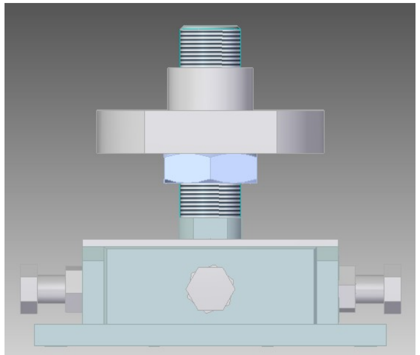
1. Reduce the distance between the adjustment mechanism and the beam center

2. Increase the contact surface of the adjustment mechanism

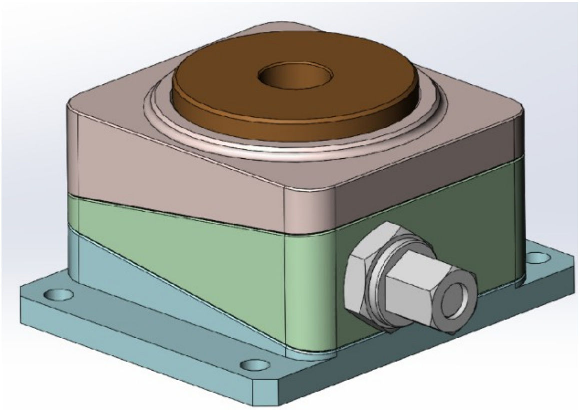
# Adjustment Mechanisms



3-D , Layered
Range:±20mm
Precision:~20μm

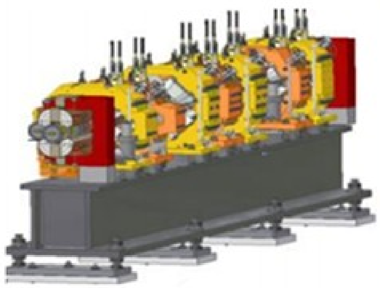


3-D , Integrated
Range:±20mm
Precision:~20μm

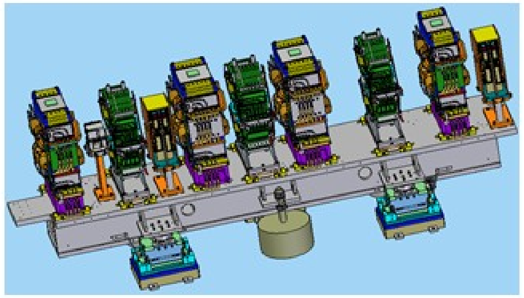


Vertical direction , wedge
Range:<±10mm
Precision:~5μm

# Girder Support Systems

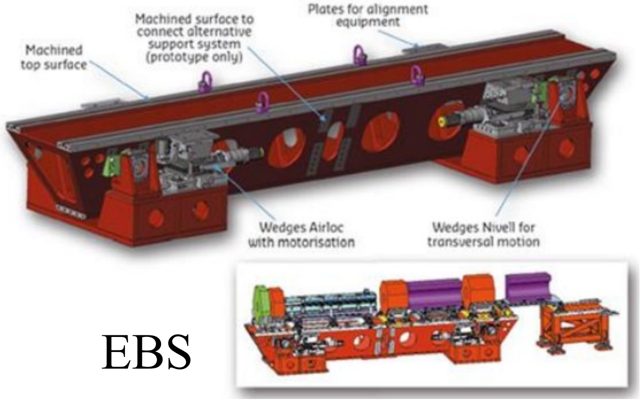


NSLS-II



SSRF

EBS




*f*=30Hz

*f*=27Hz

*f*=42Hz

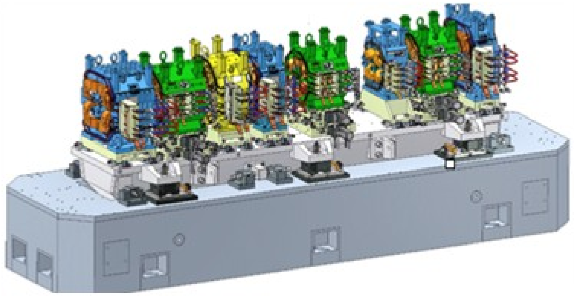
Pedestals with Bottom Support

Pedestals with Side Support

# Girder Support Systems

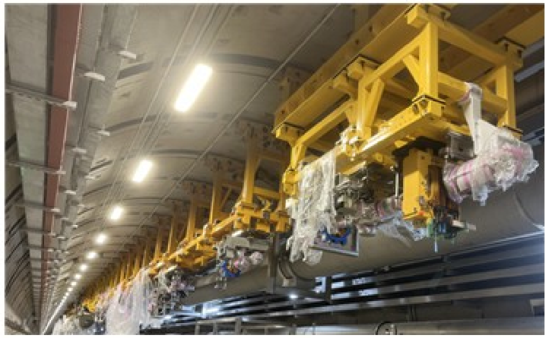
SIRIUS

*f*>100Hz



HEPS

*f*=54Hz



SHINE

*f*=~20Hz

Plinth with Side Support

Suspension support

# Alignment

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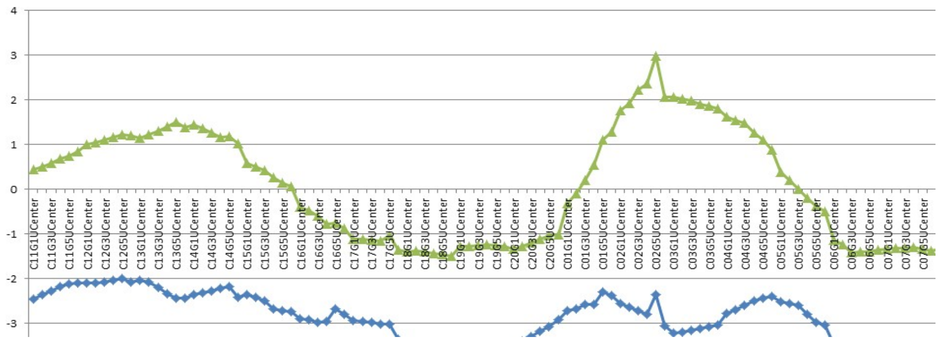
Alignment is to provide a relatively **smooth** orbit under absolute accuracy for the electron beam and beamline. Using geometric measurement methods, the component is adjusted to the correct position through instrument measurement, providing a preliminary orbit for facility.

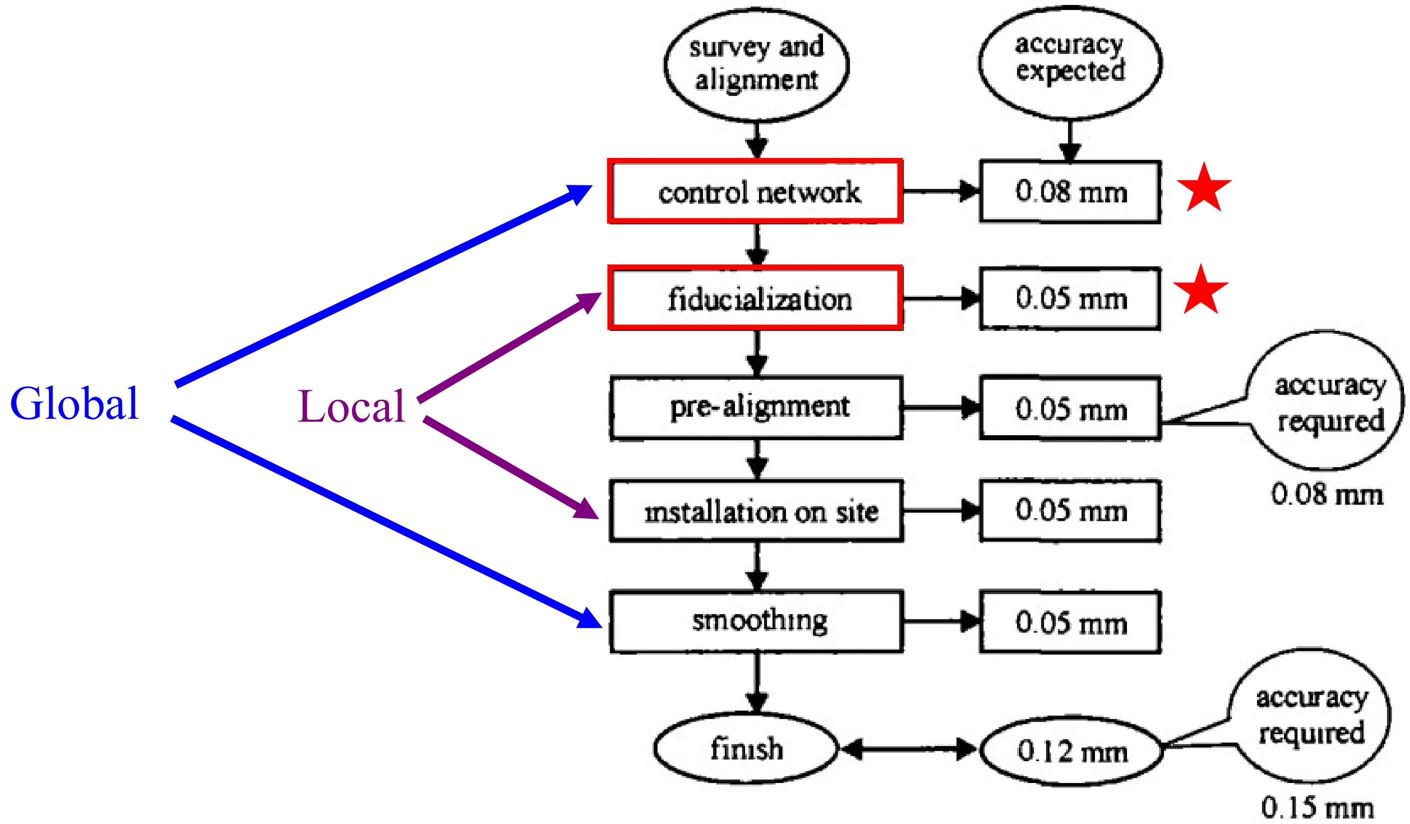
| | Component | Relative accuracy/mm(rms) | | | Absolute accuracy/mm | | Angle error/mrad | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ΔX | ΔY | ΔZ | ΔX | ΔZ | Roll | Pitch | Yaw |
| Linac 1400m | Cryomodule | 0.3 | 2 | 0.3 | 2 | 2 | 2 | 0.05 | 0.05 |
| | Quadrupole | 0.1 | 0.5 | 0.1 | 2 | 2 | 1 | 5 | 5 |
| | Dipole | 0.1 | 0.1 | 0.1 | 2 | 2 | 1 | 5 | 5 |
| | Kicker | 0.1 | 0.1 | 0.1 | 1 | 1 | 1 | 1 | 1 |
| Undulator 400m | Undulator | 0.1 | 0.5 | 0.1 | 0.25 | 0.25 | 1 | 0.1 | 0.1 |
| | SC undulator | 0.1 | 0.5 | 0.1 | 0.25 | 0.25 | 1 | 0.1 | 0.1 |
| | Phase shifter | 0.1 | 0.5 | 0.1 | 0.25 | 0.25 | 1 | 1 | 1 |
| | Quadrupole | 0.1 | 0.5 | 0.1 | 0.25 | 0.25 | 1 | 5 | 5 |
| The whole facility <3mm/3km | | | | | | | | | |

**Alignment requirement in SHINE**




**Alignment accuracy of quadrupoles in SSRF ring**

# Alignment Process

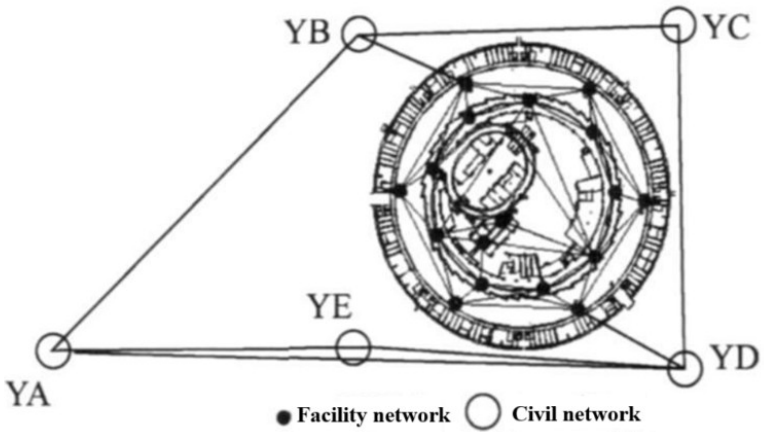


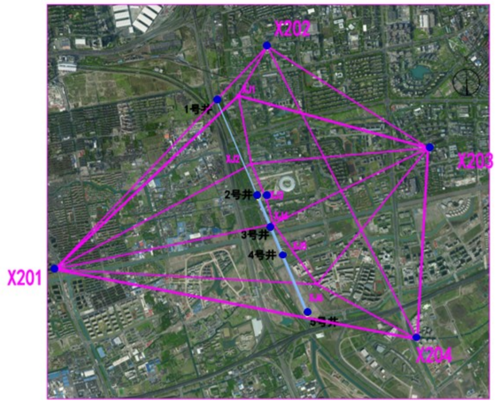
# Control network

The alignment control network is generally arranged in stages, with primary control network distributed throughout the overall control network of each part of the facility to ensure the correct absolute relationship between each part， and control the accumulation of errors in the secondary control network, mainly to ensure the absolute accuracy of c omponents.

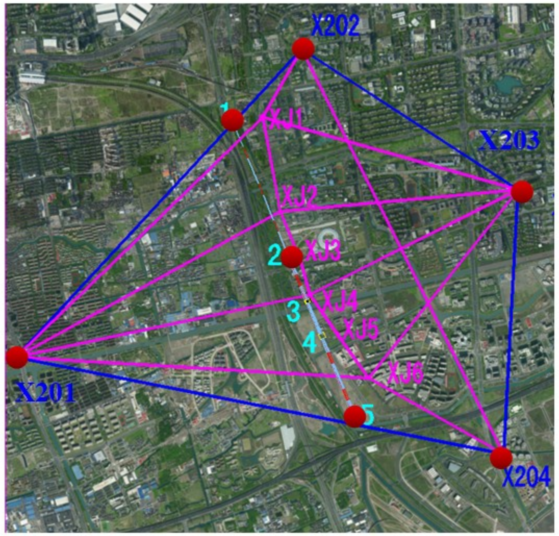
Civil engineering primary control network: Used for civil construction

Facility primary control network: Used for facility components installation



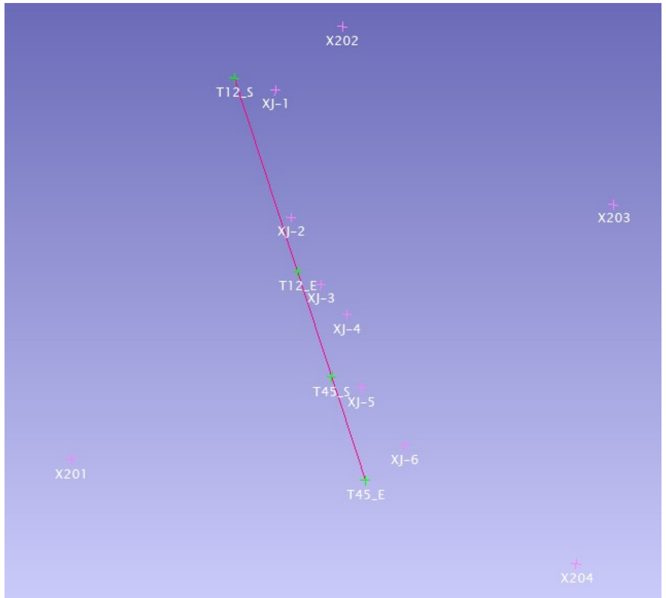



# Primary control network




Shanghai urban coordinate system

| | 北/mm | 东/mm |
|---|---|---|
| XJ-1 | -3817726 | 10420165 |
| XJ-2 | -4702497 | 10578462 |
| XJ-3 | -5160705 | 10811064 |
| XJ-4 | -5359020 | 11005645 |
| XJ-5 | -5868395 | 11136993 |
| XJ-6 | -6253378 | 11461375 |
| X201 | -6485638 | 9130025 |
| X202 | -3345621 | 10869832 |
| X203 | -4485851 | 12835801 |
| X204 | -7017341 | 12706506 |
| T12_S | -3749661 | 10127612 |
| T12_E | -5083157 | 10644030 |
| T45_S | -5803991 | 10923185 |
| T45_E | -6512702 | 11197645 |




Civil engineering primary control network :XJ1-XJ6 、X201-X204

The coordinates were provided by Shanghai surveying and mapping institute

Tunnel central axis:T12_S、T12_E、T45_S、T45_E

The coordinates were provided by architectural design institute

# Primary control network

The spatial scope of the primary control network is extensive, GNSS or total stations are used for horizontal control network measurement, while level is employed for vertical control network measurement.

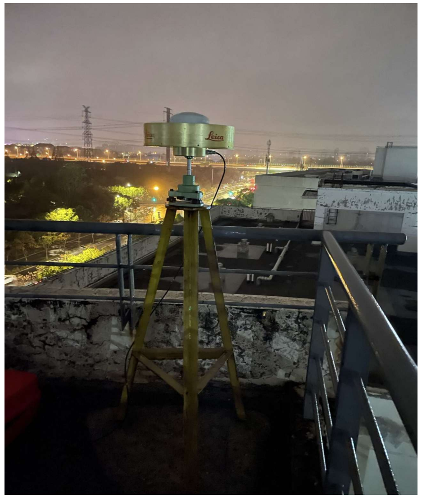
**Total Station**


**GNSS**

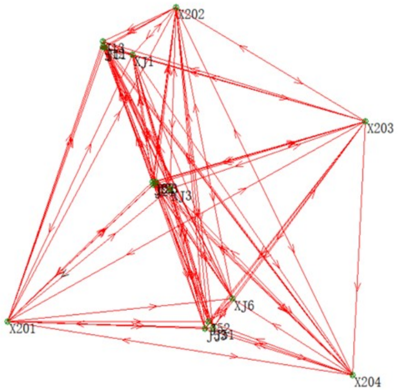
**Level**

# Primary control network

We used GNSS to simultaneously observe the civil engineering primary control network and the SHINE primary control network



Civil engineering and facility primary control network




平差坐标(X, Y)

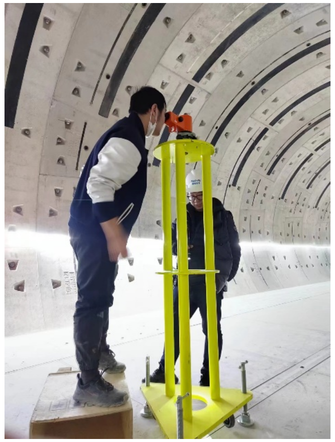
| No. | Name | X(m) | Y(m) | Mx(cm) | My(cm) | Mp(cm) |
|---|---|---|---|---|---|---|
| 1 | X202 | -3345.6210 | 10869.8320 | | | |
| 2 | J1W | -3748.5059 | 10127.7919 | 0.10 | 0.09 | 0.13 |
| 3 | J21 | -5087.7863 | 10663.4769 | 0.13 | 0.12 | 0.17 |
| 4 | J22 | -5169.9611 | 10664.9724 | 0.15 | 0.14 | 0.21 |
| 5 | J23 | -5091.6080 | 10629.5525 | 0.17 | 0.15 | 0.23 |
| 6 | J51 | -6503.6531 | 11219.1081 | 0.11 | 0.10 | 0.15 |
| 7 | J52 | -6581.1115 | 11238.4341 | 0.11 | 0.10 | 0.15 |
| 8 | J53 | -6570.5916 | 11191.1721 | 0.13 | 0.12 | 0.18 |
| 9 | X201 | -6485.6215 | 9130.0367 | 0.10 | 0.10 | 0.14 |
| 10 | X203 | -4485.8302 | 12835.7831 | 0.10 | 0.10 | 0.14 |
| 11 | X204 | -7017.3133 | 12706.4922 | 0.11 | 0.10 | 0.15 |
| 12 | XJ3 | -5160.6848 | 10811.0674 | 0.10 | 0.09 | 0.14 |

最弱点

| No. | Name | MX(cm) | MY(cm) | MP(cm) |
|---|---|---|---|---|
| 5 | J23 | 0.17 | 0.15 | 0.23 |

Accuracy better than 3mm

# Primary control network




平差坐标及其精度

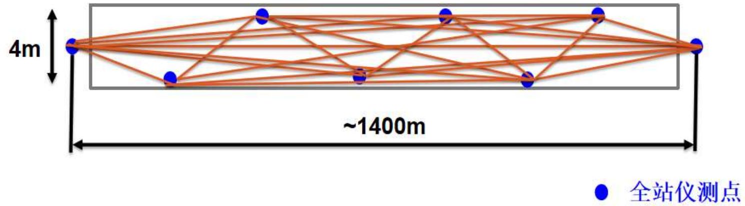
| Name | X(m) | Y(m) | MX(cm) | MY(cm) | MP(cm) | E(cm) | F(cm) | T(dms) |
|---|---|---|---|---|---|---|---|---|
| S1 | 0.0000 | 0.0000 | | | | | | |
| S8 | 1402.5228 | 0.0000 | | | | | | |
| S4 | 603.2640 | -0.7977 | 0.035 | 0.038 | 0.052 | 0.038 | 0.035 | 90.1222 |
| S5 | 801.5880 | 0.7712 | 0.035 | 0.038 | 0.052 | 0.038 | 0.035 | 90.1312 |
| S2 | 200.7053 | -1.2533 | 0.036 | 0.031 | 0.048 | 0.036 | 0.031 | 179.2336 |
| S3 | 398.9952 | 0.3477 | 0.036 | 0.036 | 0.050 | 0.036 | 0.036 | 89.0607 |
| S6 | 999.8811 | -0.3907 | 0.035 | 0.036 | 0.050 | 0.036 | 0.035 | 89.5147 |
| S7 | 1198.1312 | 1.1595 | 0.035 | 0.030 | 0.047 | 0.035 | 0.030 | 179.4533 |
| S9 | 1426.5655 | 1.3812 | 0.063 | 0.009 | 0.063 | 0.063 | 0.008 | 3.3520 |

Mx均值：0.04　　My均值：0.03　　Mp均值：0.05

最弱点及其精度

| Name | X(m) | Y(m) | MX(cm) | MY(cm) | MP(cm) | E(cm) | F(cm) | T(dms) |
|---|---|---|---|---|---|---|---|---|
| S9 | 1426.5655 | 1.3812 | 0.063 | 0.009 | 0.063 | 0.063 | 0.008 | 3.3520 |

**Accuracy better than 1mm**

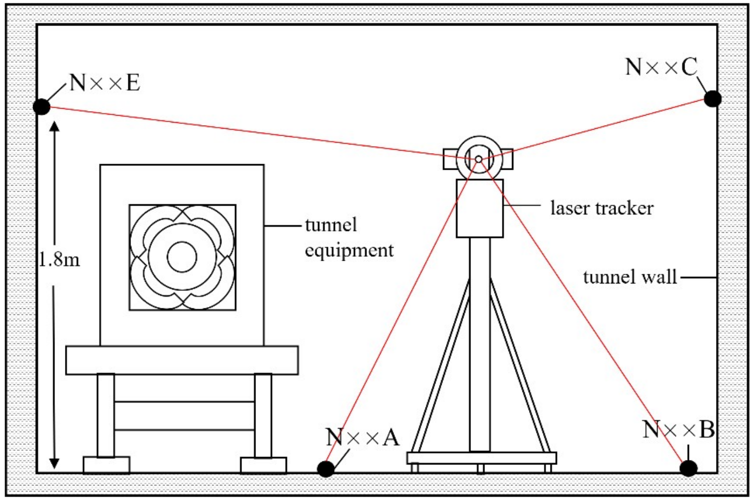



Narrow and elongated linear control network

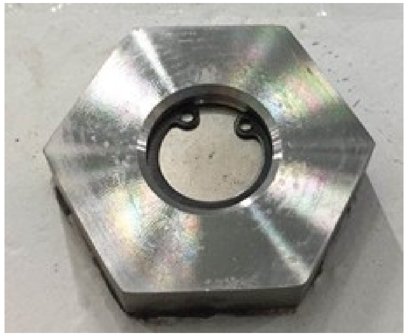
direction observation in rounds

# Secondary control network

The secondary control network ensures the relative accuracy of accelerator components. The control network has to be established with stable target marks at intervals of about 6-10 m, the target marks have to be installed at variable heights from floor to top, forming an envelope for the components.




Layout of target marks

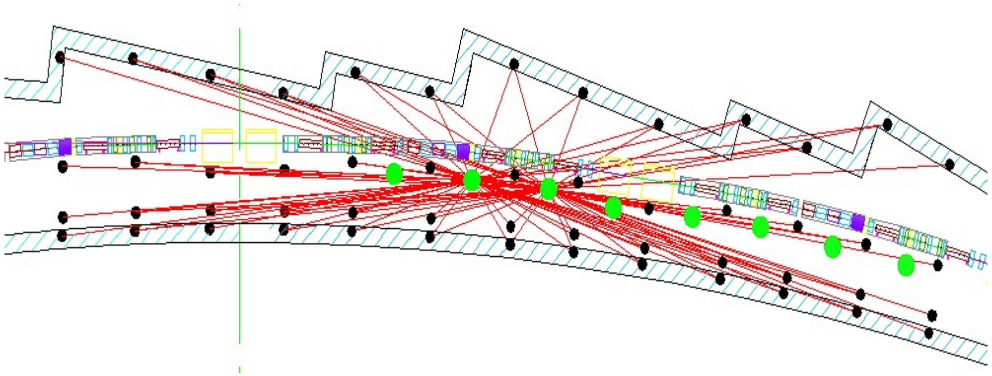


Top target marks

Floor target marks

# Second control network

Using laser tracker to conduct full-field, high-precision measurement of the secondary control network， at each measurement station, 6-8 sections of control points are measured on both sides, with a spacing of 15-20 meters between stations. This measurement method ensures that there are sufficient common points between adjacent stations for overlap and smoothness of the control network, and it is also a necessary condition for ensuring the relative accuracy of the components.



Second control network measurement

Laser tracker

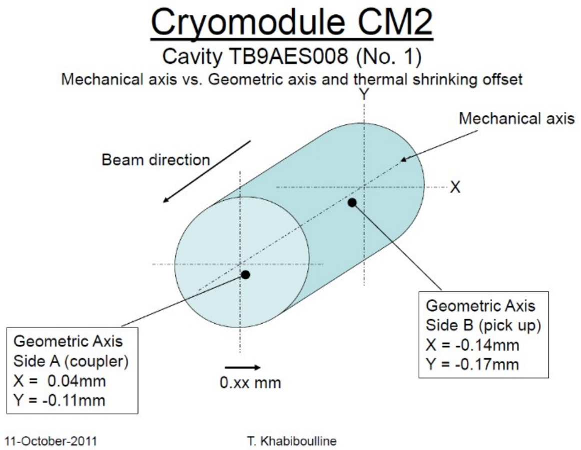
# Fiducialization

Fiducialization is the transfer of the mechanical or physical center of the component to external target marks, which are used for subsequent on-site installation and re_alignment. when designing components, it is necessary to establish a measurement reference, which can be used to measure and obtain the mechanical center of component.

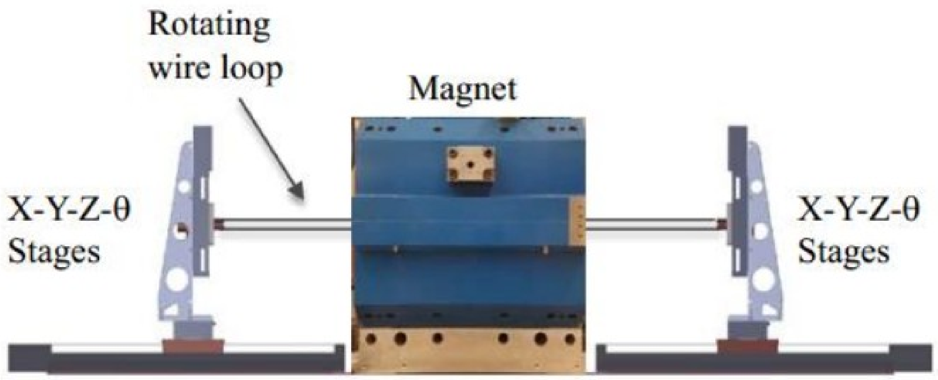
**Fiducilisation of the mechanical center of magnet**

# Fiducialization

There may be deviations between the mechanical center and the physical center of components , therefore,components requiring high alignment accuracy are usually fiducialized with physical centers, including electrical or magnetic centers




**Fiducilisation of the electrical center of superconducting cavity**

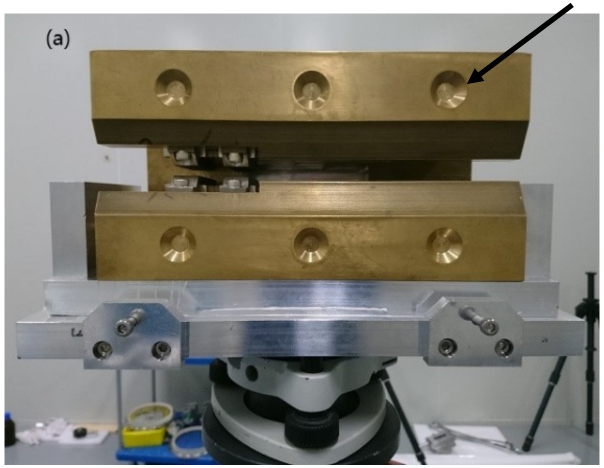



**Fiducilisation of the magnetic center of magnet**

# Fiducialization

The magnetic landmark consists of several permanent magnets which can generate a normal and a skew quadrupole field with high gradient in two directions. Positions of zero point of the two quadrupole fields horizontal component were measured and transferred to external target marks.

Target mark

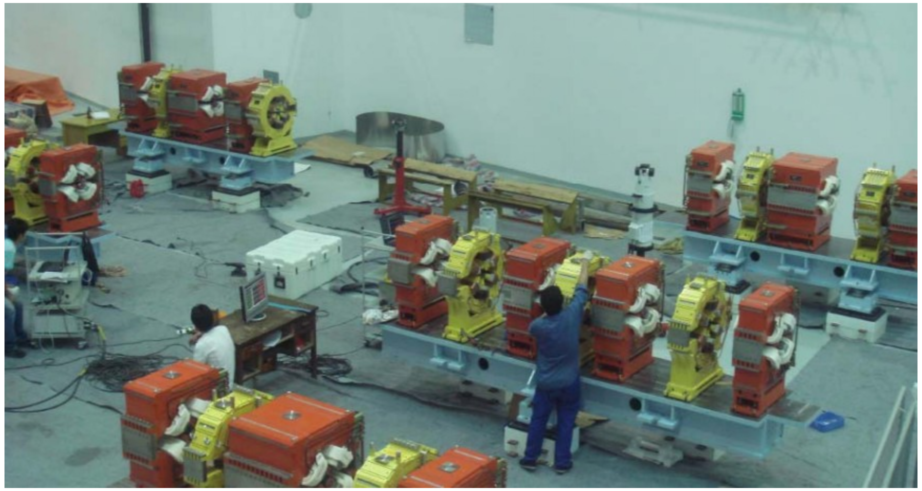


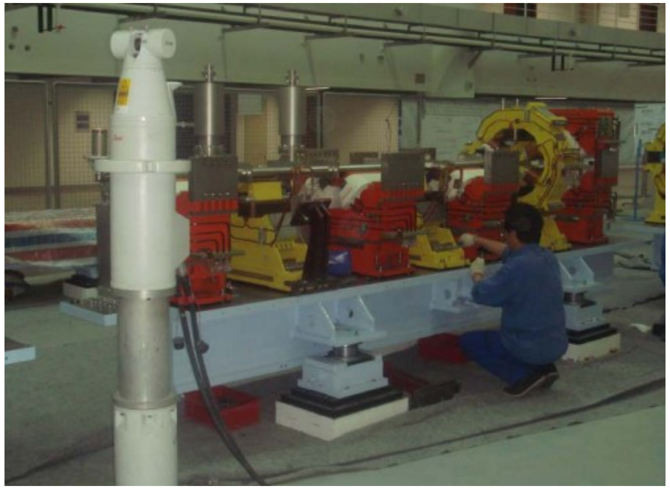

**Magnetic landmark**

**Fiducilisation of the magnetic center of undulator**

# Pre_alignment

The magnets and vacuum chambers are placed on a girder, which facilitates offline pre_alignment, ensures the relative relationship between components, and improves installation efficiency and accuracy.

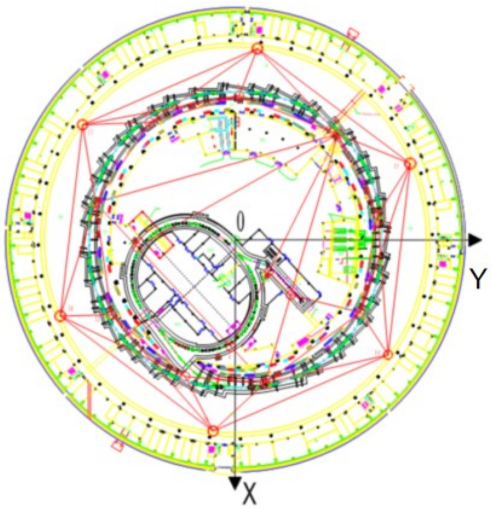




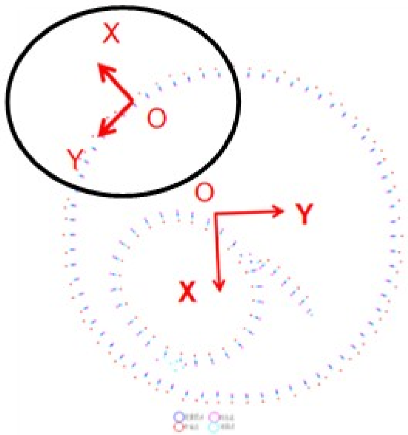
**Pre_alignment of the magnet and vacuum chamber**

# Installation on site

Unifying the user coordinate system(UCS) with the lattice coordinate system(LCS) and the facility coordinate system(FCS)

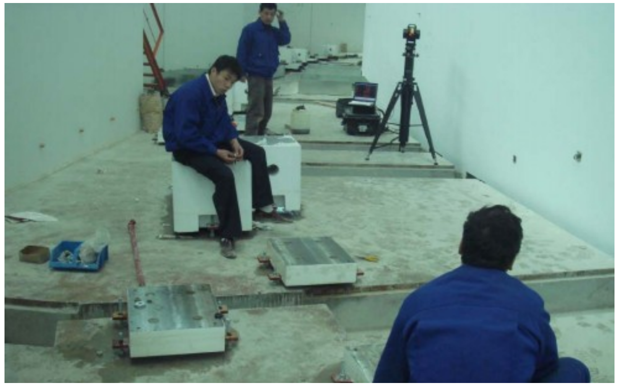



**Unifying coordinate system**




**Local coordinate system**

# Installation on site



Staking out

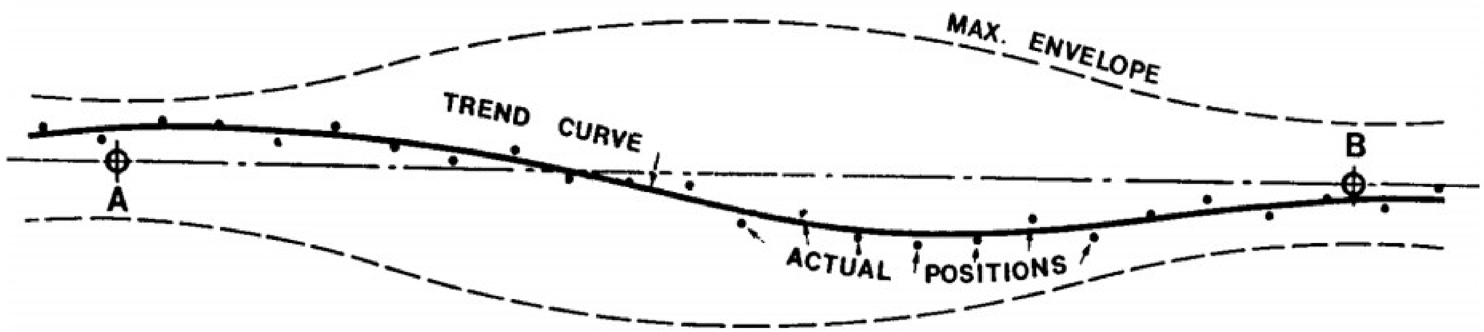
Base alignment

Girder alignment

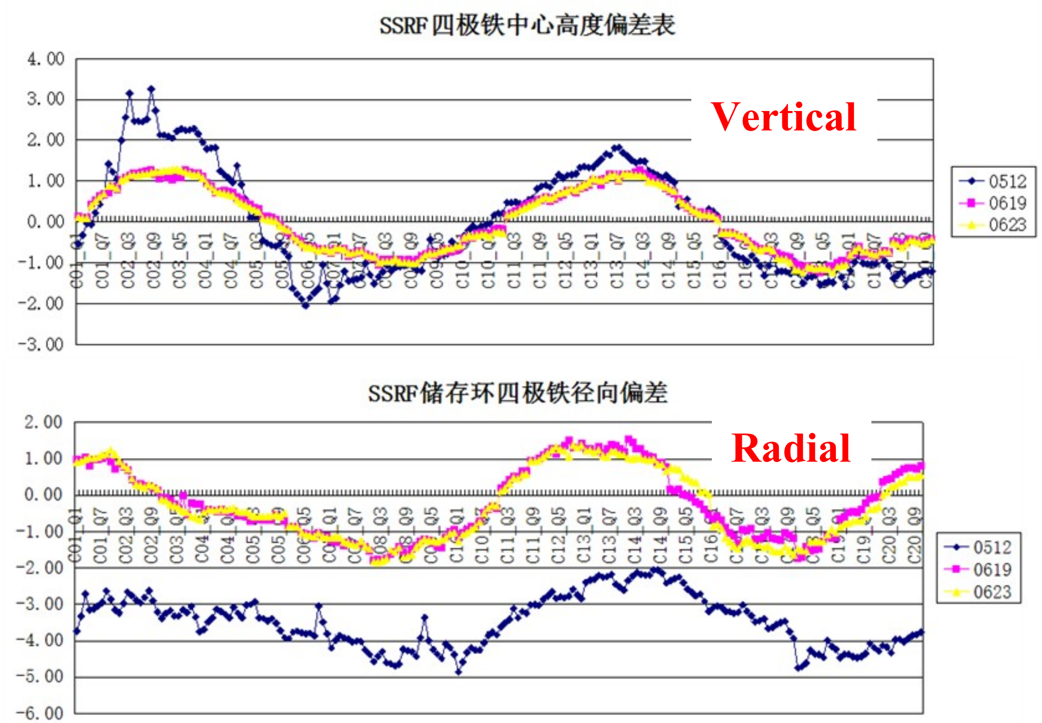
# Smoothing

The installation cycle of the components is relatively long, and the foundation deformation is large in the early stage. Therefore, after the component installation is completed, an overall measurement will be conducted to obtain the component deviation.

The electron beam is concerned with the smoothness of the orbit. When realigning, adjustments are made to components with large relative deviations within the allowable range of absolute accuracy



# Smoothing




Re_alignment of the SSRF Ring

Electron beam orbit deviation：280&280→ 50/55μm(rms)

1.Overview

2.Mechanical Stability

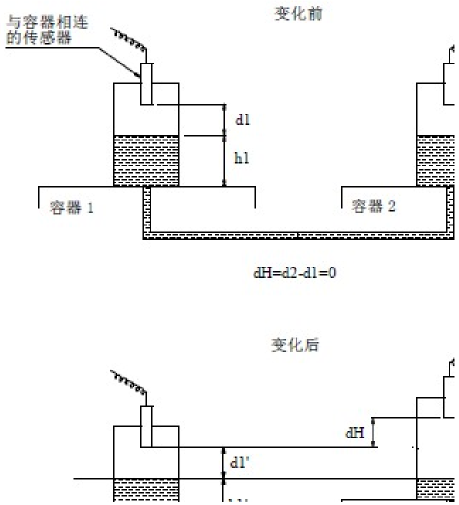
3.Alignment

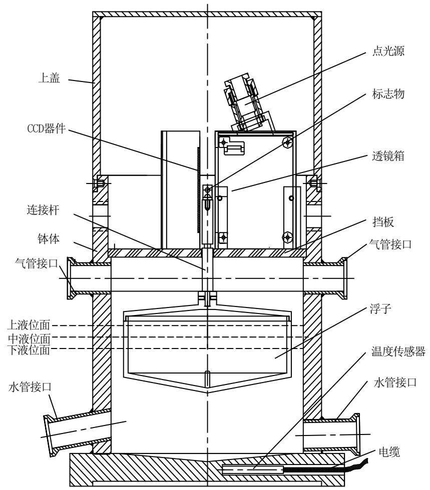
4.Monitoring deformation

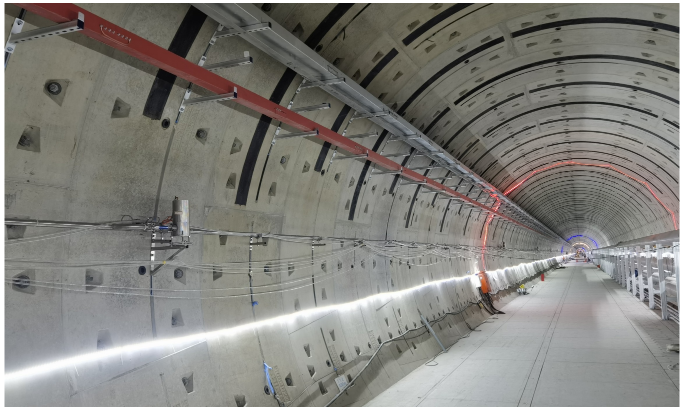
4.Summary

# Hydrostatic Levelling System

The Hydrostatic Leveling System (HLS) uses the principle of connectors to monitor real-time changes in the vertical direction of foundations or components, with a measurement accuracy of 0.01-0.05mm

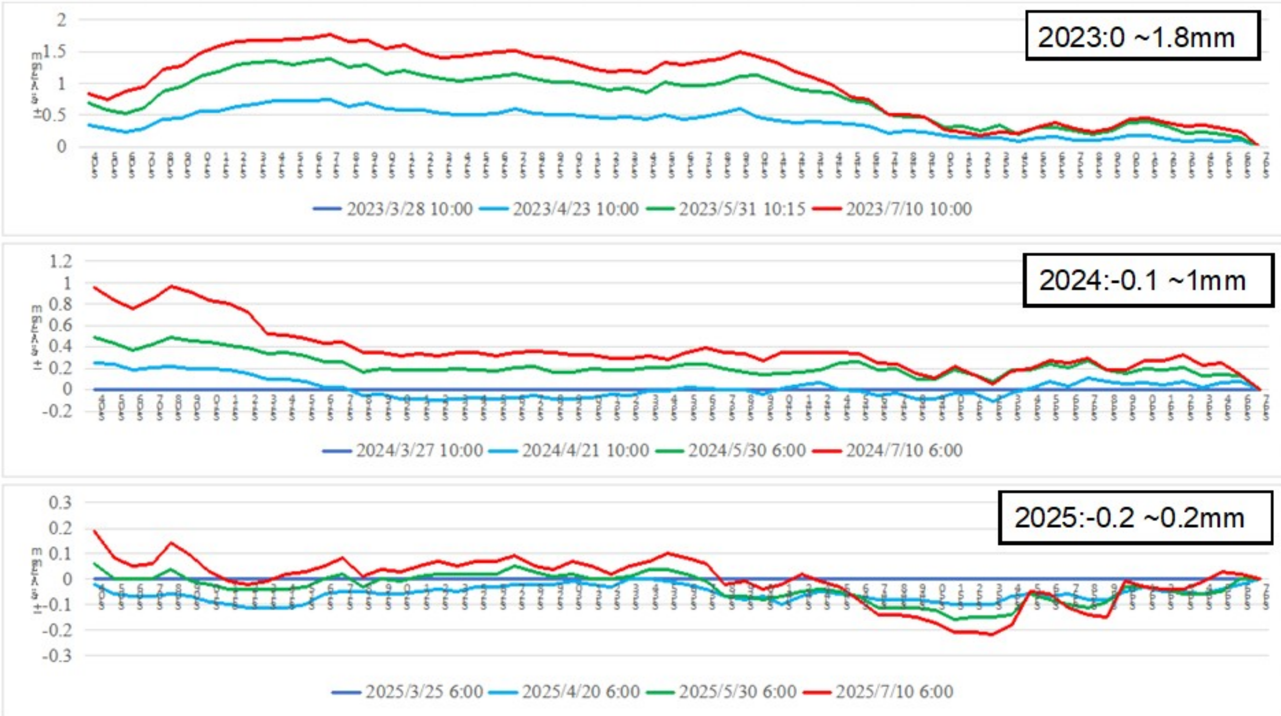


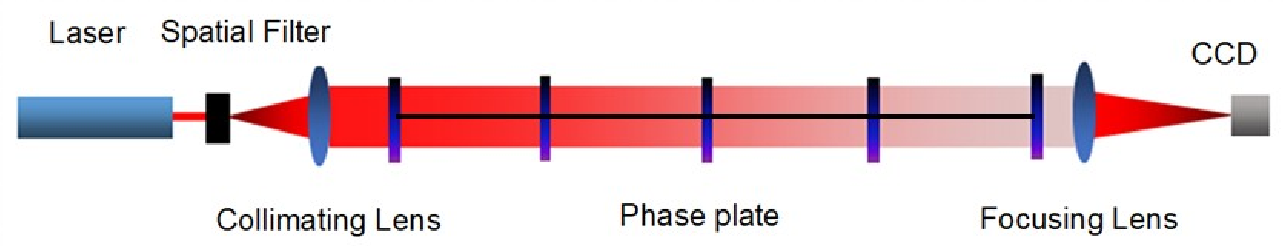
# Hydrostatic Levelling System

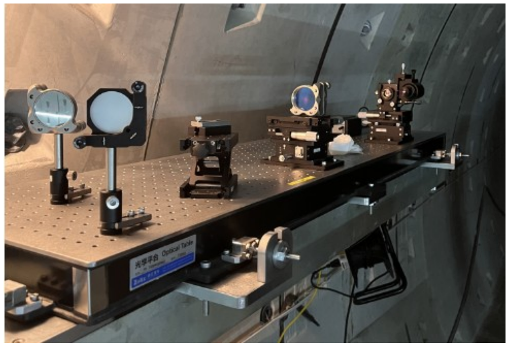
The SHINE 1.5 km linac tunnel has been continuously monitored by HLS for more than 3 years, and it has been found that the settlement convergence of the tunnel has improved, and the relative change amplitude has gradually decreased



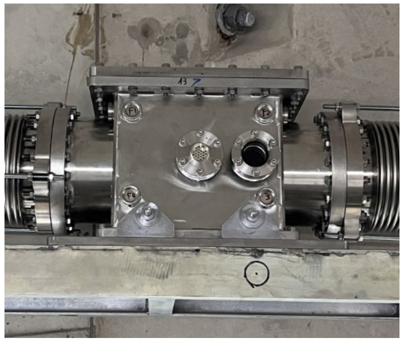
# Vacuum laser alignment system

Ensure absolute straightness of components in the undulator tunnel
Monitor the uneven deformation in the horizontal and vertical directions

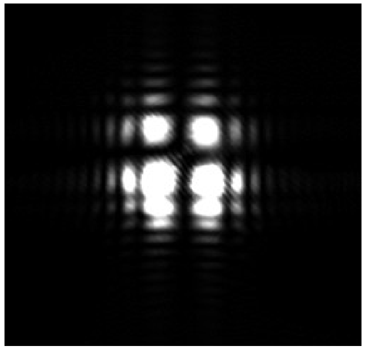


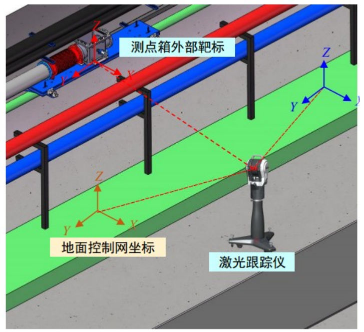
**Transmitting end**



**Measurement box**



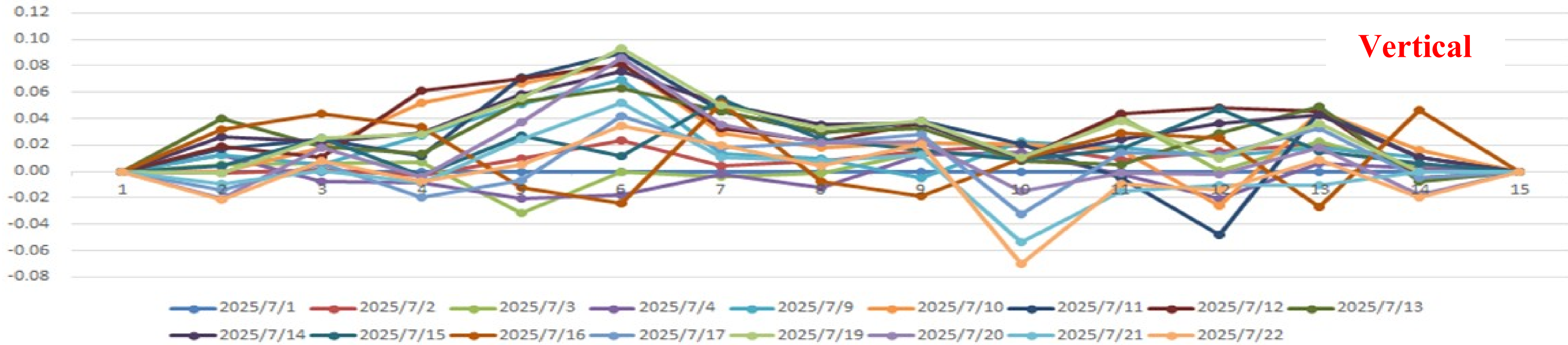
**Imaging on CCD**

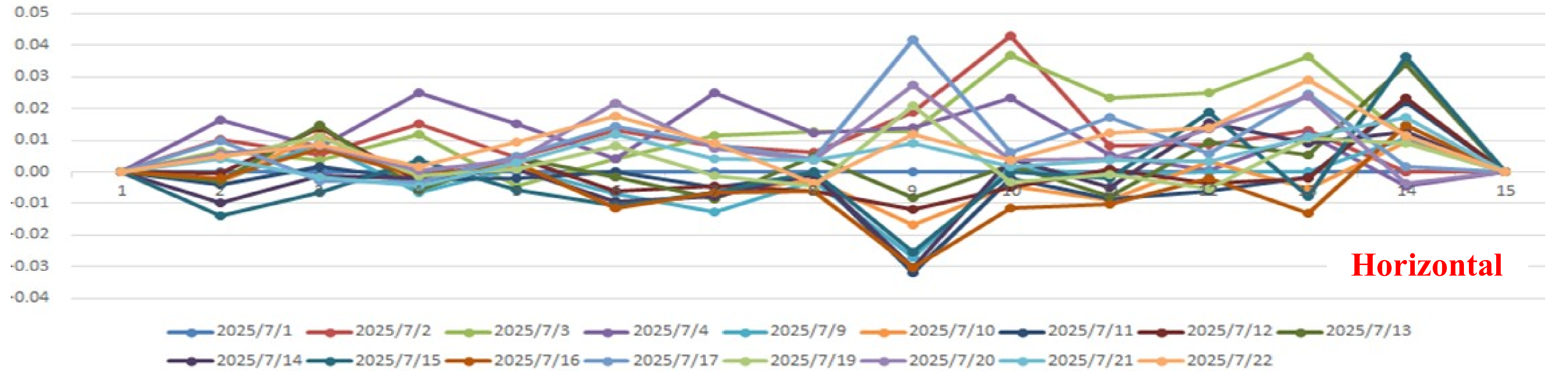



**Joint measurement**

# Vacuum laser alignment system

中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

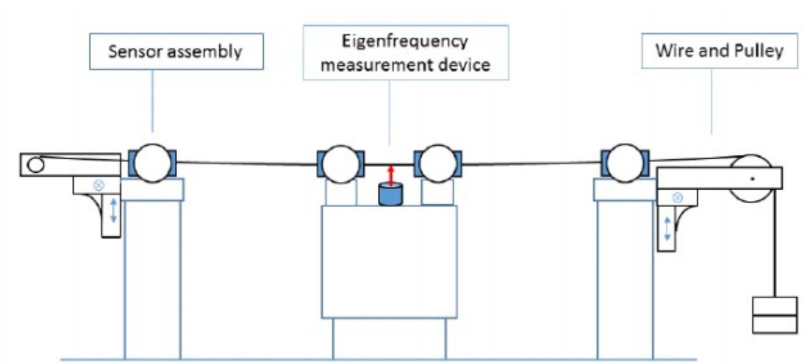


# Wire Postion Monitor

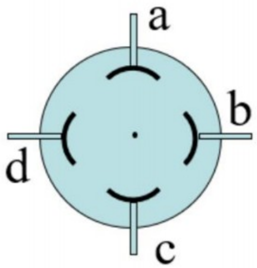
中國科學院 上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

The principle of the wire position monitor is similar to the directional coupler BPM, o btaining displacement change curves and shrinkage amounts during the cooling process of superconducting cavities and quadrupole

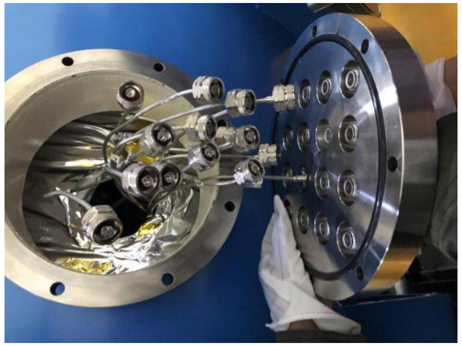



Probe

Counterweight




The principle of the wire postion monitor



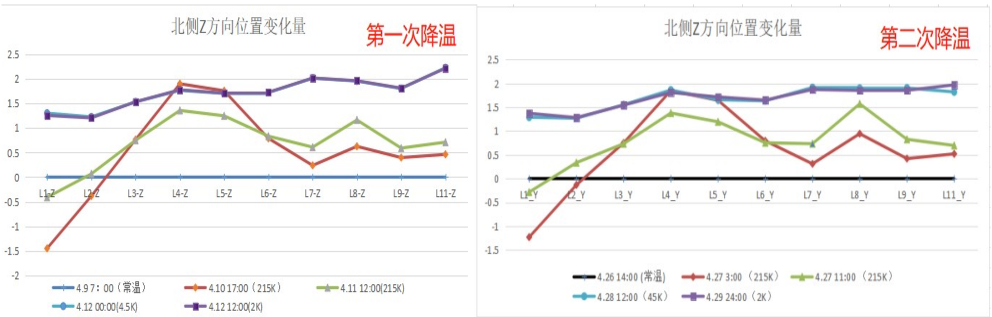
Cable

Collector

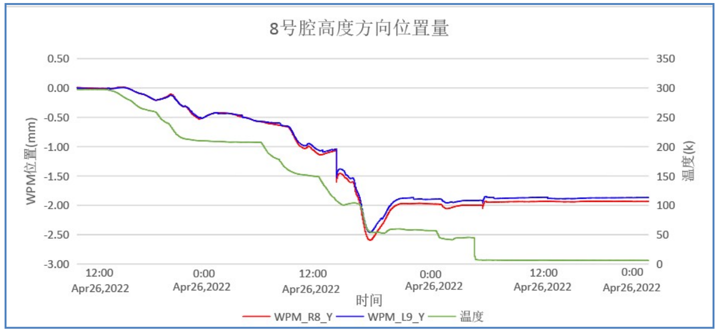
# Wire Postion Monitor

Wire Postion Monitor has been successfully operated to monitor displacements in SHINE

Optimize the cooldown and warm up procedures of cryomodule




Measurement results after two cooling cycles




Cavity deformation during cooling process

## Summary

Mechanical stability and accuracy are the two major tasks and goals of accelerator mechanical engineering

Controlling the environmental conditions is critical to meeting the design goals

Alignment is a strict, complex, and detailed process that strictly controls the errors in every step

Deformation monitoring is also an important task and provides displacement ref erence for commission

# References

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Mechanical Effects on Beam Stability,June-RongChen,MEDSI ’04, ESRF, May 24, 2004

粒子加速器机械工程，殷立新，OCPA-2016，上海，2016.08.03

高能同步辐射光源(HEPS)进展和准直概述,董岚，第九届全国粒子加速器准直安装及机械设计学术研讨会，惠州，2025.06.24

# Homework

How to achieve good mechanical stability and alignment of accelerator？

# Thanks for your attention