Design and Testing of HEPS Storage Ring Magnet Support System

Zihao Wang, Chunhua Li, Haijing Wang, Shu Yang, Lei Wu, Siyu Chen, Yuandi Xu, Shang Lu, Xiaoyang Liu, Minxian Li, Ningchuang Zhou

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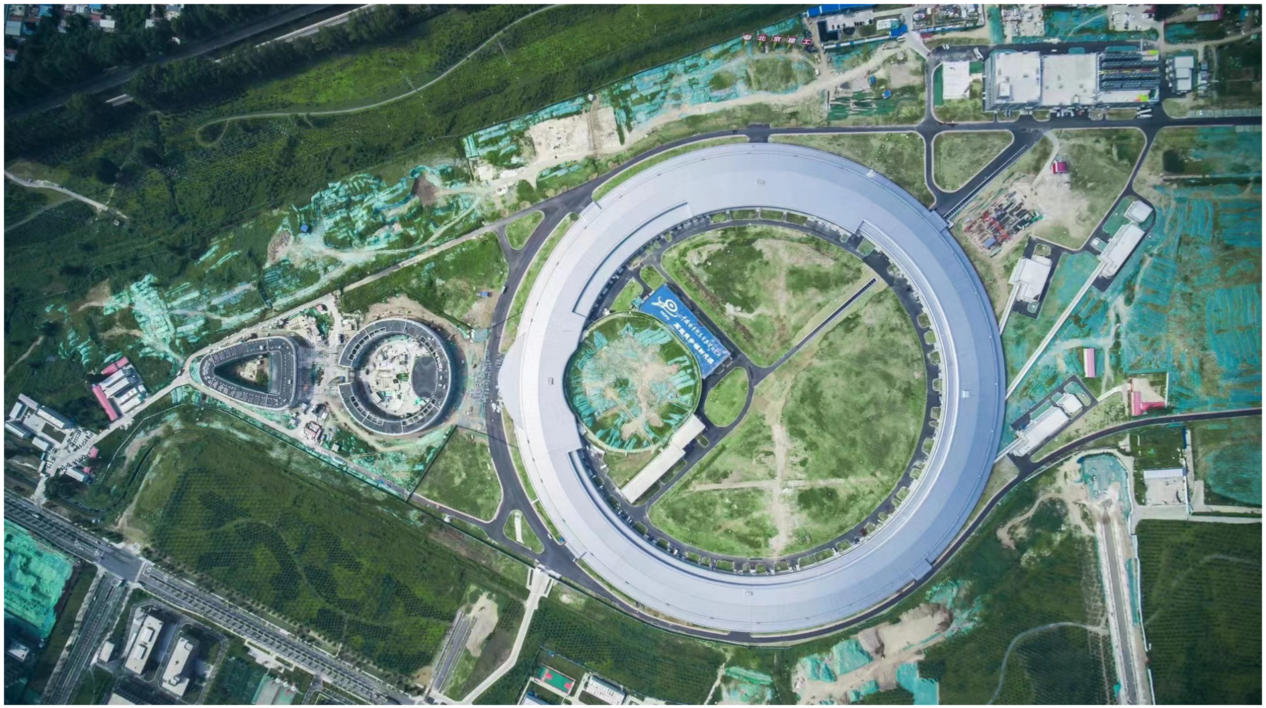
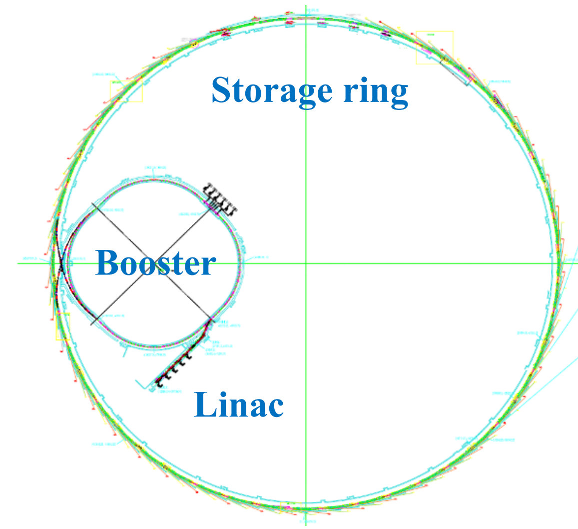
Outline

Introduction

HEPS: High Energy Photon Source, 2019.6-2025.12， Huairou, Beijing





- *High energy: 6GeV*
- *low emittance： 60pm·rad*
- *circumference: 1360.4m*

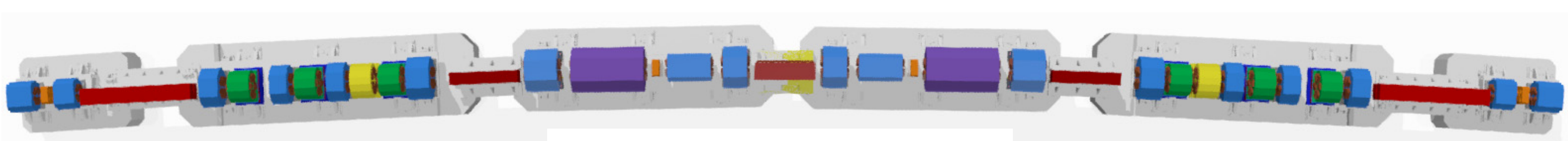


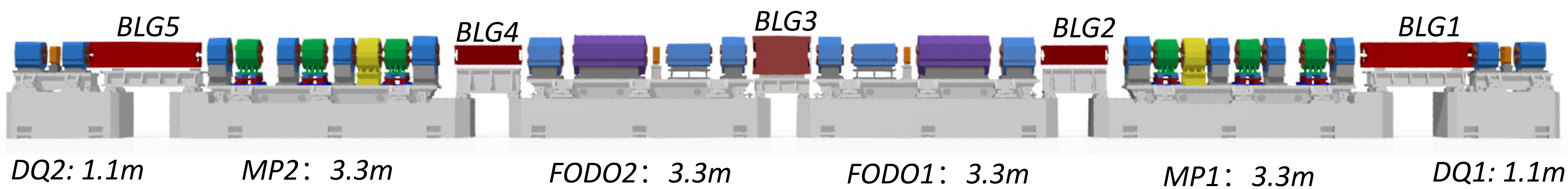
Fig.1 One arc section(1/48)

Introduction

- *Multipole magnets will be pre-aligned on girders and then installed in the tunnel.*
  - *6 pre-alignment M&G modules of 3 types.*
    - *FODO * 2, MP * 2, DQ * 2*
  - *5 dipole(BLG) separate girders supported on the concrete plinths*

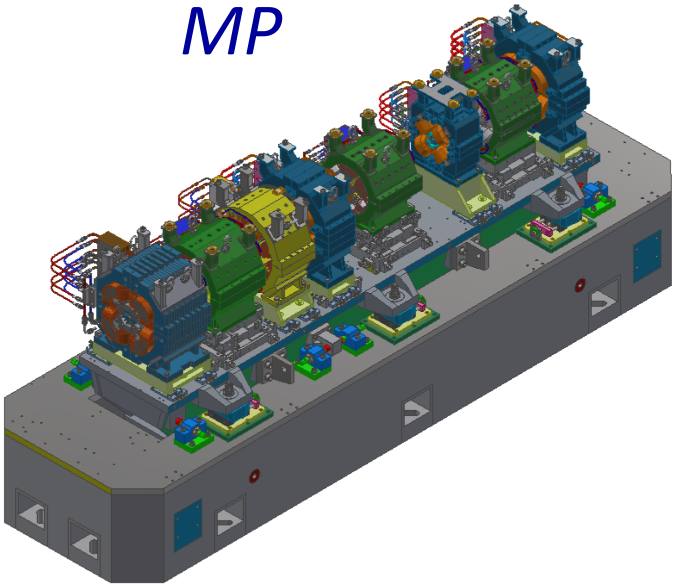
Parameters		*Requirement*
Alignment tolerance between girders	*Transverse (X)*	*±0.05mm*
	Vertical (Y)	*±0.05mm*
	Longitudinal(Z)	*±0.15mm*
Natural frequency of M&G assembly		*54Hz*

➢ *Sextupoles be capable of being aligned online, for correction of beam optical parameters.*

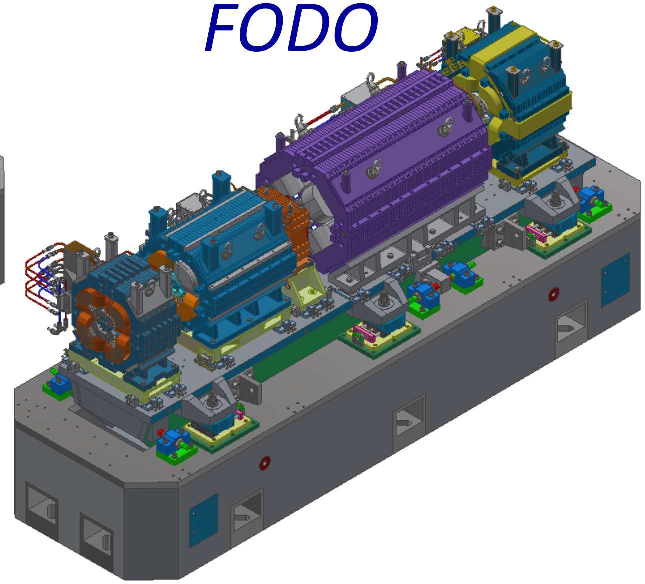


Introduction

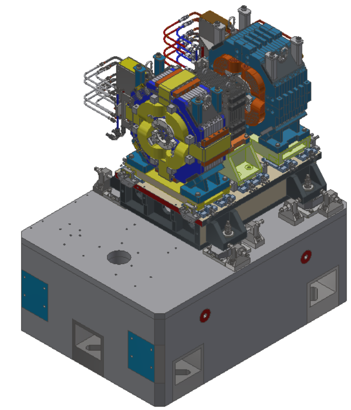
MP



FODO



DQ



Type	Number	Length	Weight (Girder+ Plingth)	Weight (Magnet)
DQ	96	1.5m	2.8t	1.2t
MP	96	4.3m	7.3t	4.3t
FODO	96	3.8m	6.7t	6.2t

Design of Support System

- *Mechanical design requirements:*

Requirement
Ensure **alignment accuracy**
Compensate construction error *of infrastructure & Foundation settlement*
Reduce **amplification of ground vibrations**

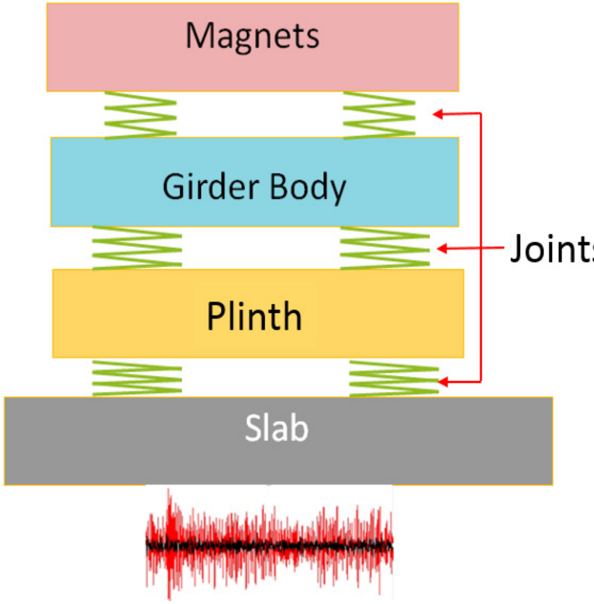
Parameters		*Values*
Resolution	*Transversal*	*≤5μm*
	Vertical	*≤5μm*
	Longitudinal	*≤15μm*
Adjusting range	*Horizontal*	*±10mm*
	Vertical	*±7mm*
Natural frequency		*≥54Hz*

- *Sensitive frequency range of HEPS beam: 5-54Hz*

- *Other considerations*：
  - *Uneven deformation of the girder with load: <20μm*
  - *As less residual internal stress as possible, to ensure the dimensional stability and keep alignment accuracy in a long term.*

Design of Support System

- *Stability is the first priority in design*
- *Magnet support system*： *magnet, girder body, plinth*
- *The stiffness of components connect with each other and contribute to the system stability.*
  - Parallel stiffness： $\frac{1}{\mathrm{K}} = \frac{1}{k1} + \frac{1}{k2} ... + \frac{1}{kn}$
  - Serial stiffness： $\mathrm{K} = k_1 + k_2 + \cdots + k_n$



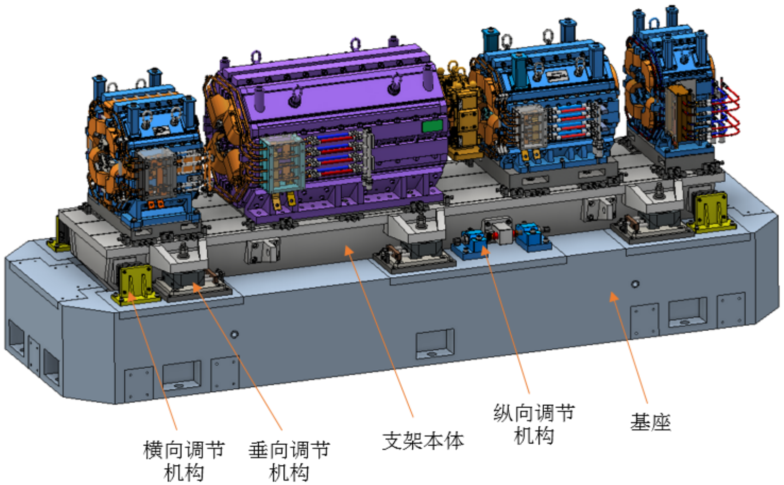
- *The connection is a weak part → high stiffness adjustment mechanism*

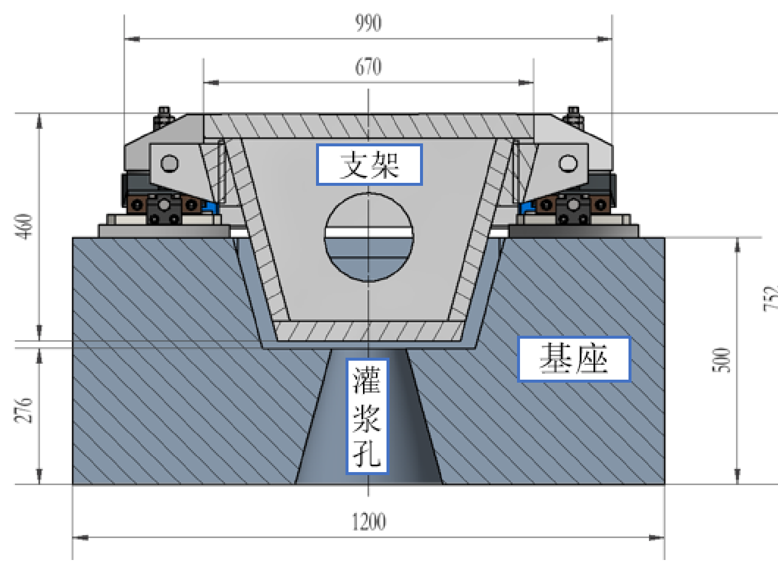
$$K = \frac{F}{\Delta L} = \frac{EA \cdot \Delta L/L}{\Delta L} = \frac{EA}{L}$$

- *The flatness and roughness has a significant effect on the stiffness→Machining accuracy*
- *Fixation of the plinth→ grouting method*

Design of Support System

- Support system structure program：
- Six-point support，box, Wedge Adjustment
    - Increase contact area, to improve connection stiffness
    - Matched girder and plinth
    - stiffness
- Ear shape support
    - The pivot point should be close to the magnetic center
    - Enlarge the transverse span of the pivot point

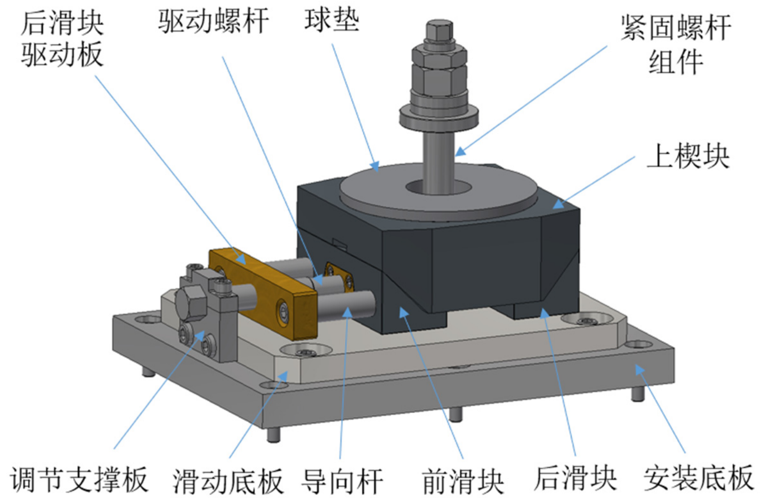


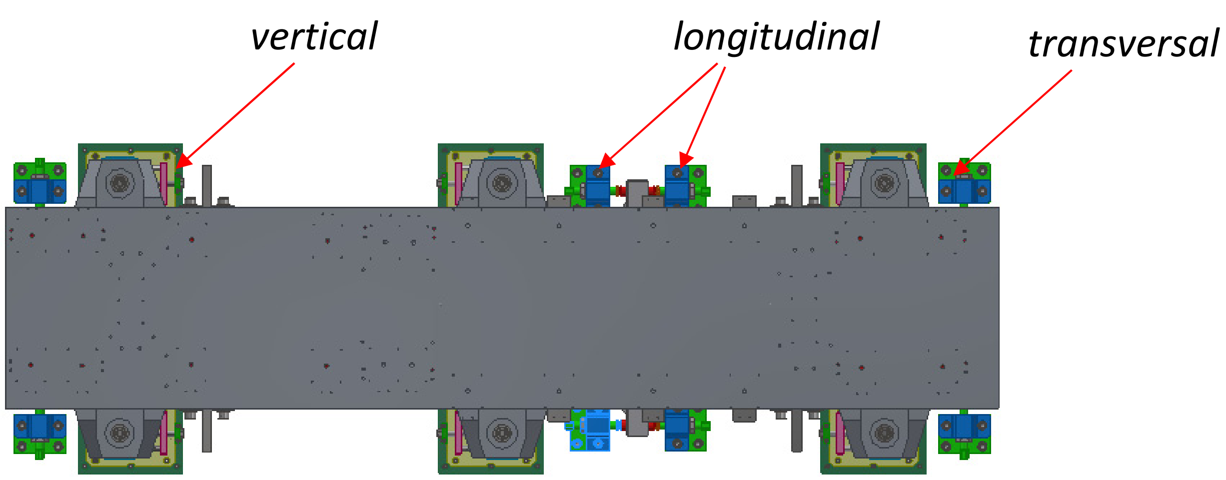


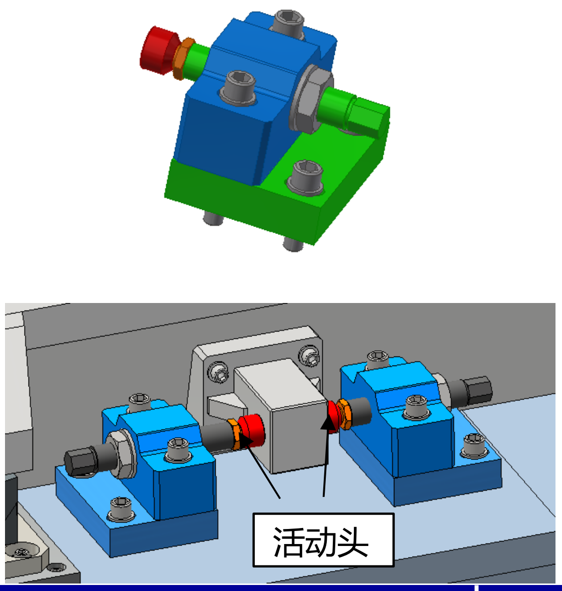
*MP/FODO*支撑系统截面图

Design of Support System

- *Location of adjustment mechanism*
  - *vertical： 6 sets， Double-wedge*
  - *transversal/ longitudinal： 2 sets each， mutual-push structure， fine thread， movable top*

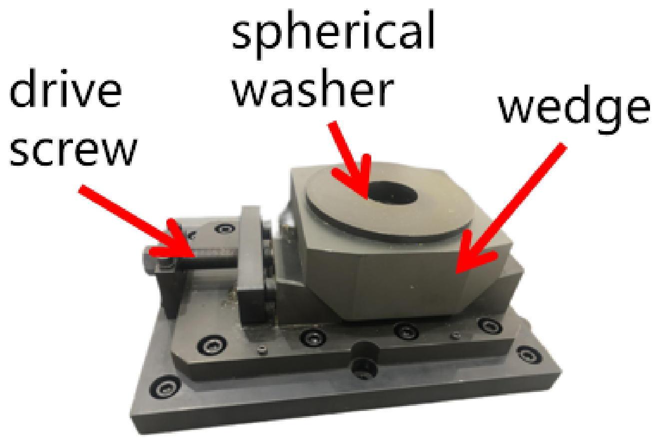


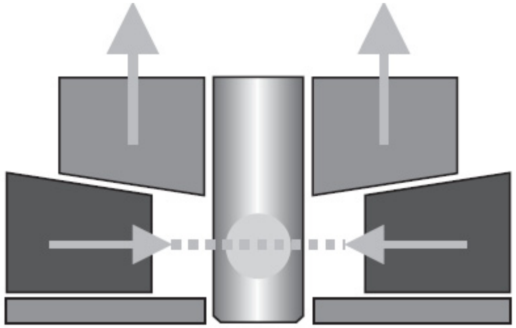




Design of Vertical Adjustment Mechanism

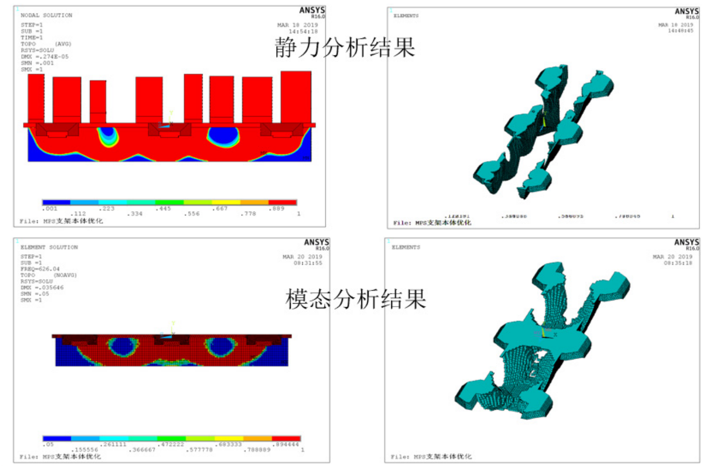
- *Vertical adjustment mechanism： key parts*
  - *Double-wedge， reduce torque for better motion performance.*
  - *Sphercial washer， adaptable to the angle of adjustment to ensure surface fit and avoid locking stress.*
- *Advantage：*
  - *Fulfill motion performance and support stiffness simultaneously*
- *Disadvantage：*
  - *Smaller adjustment range*

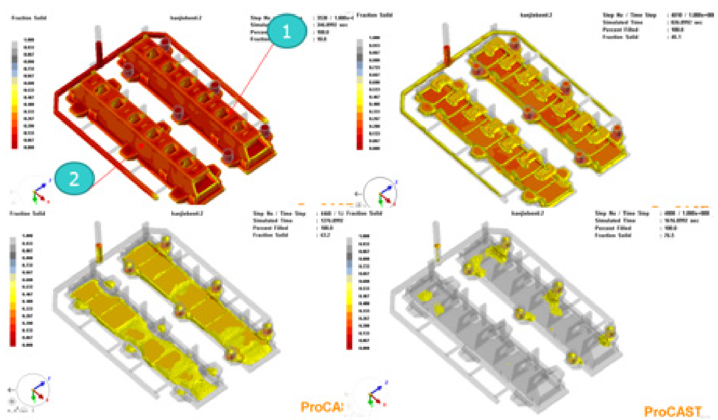




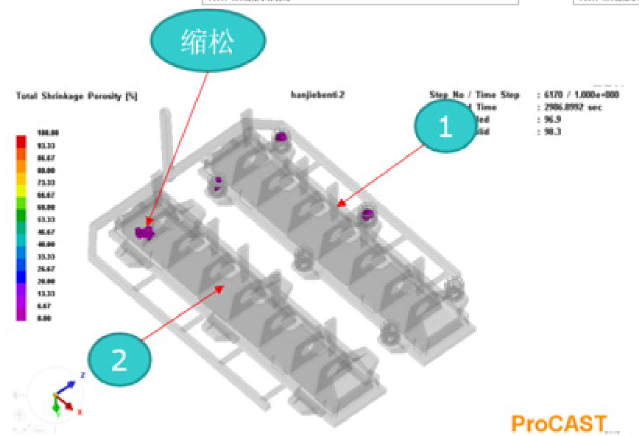
Design of Girder Body*

- *Structural optimization*： *stiffness*
  - *Cross-section shape and rib plate distribution optimization*
- *Material*： *cast iron HT350*
  - *Excellent long-term stability of dimensions; high efficiency in batch production*；
  - *Quality control is difficult*





液态收缩过程



缩松现象

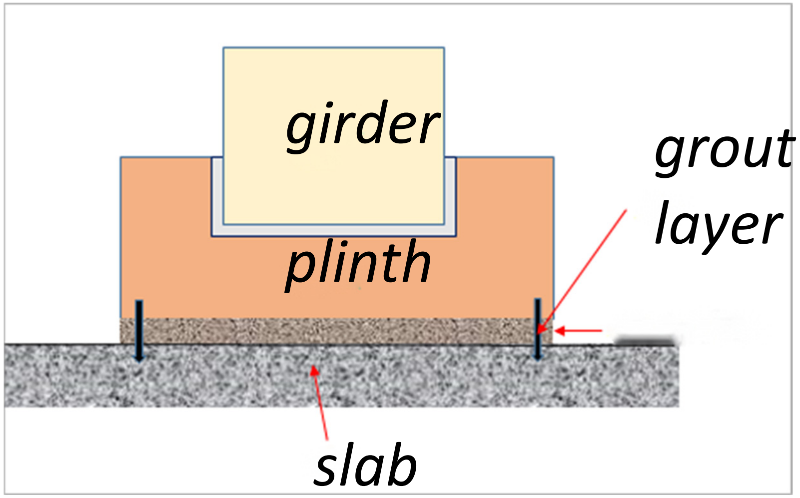
*:Chunhua Li et al., "DESIGN AND PROGRESS OF MECHANICAL SUPPORT IN HEPS", in Proceedings of IPAC2019, Melbourne, Australia, Sep. 2019.

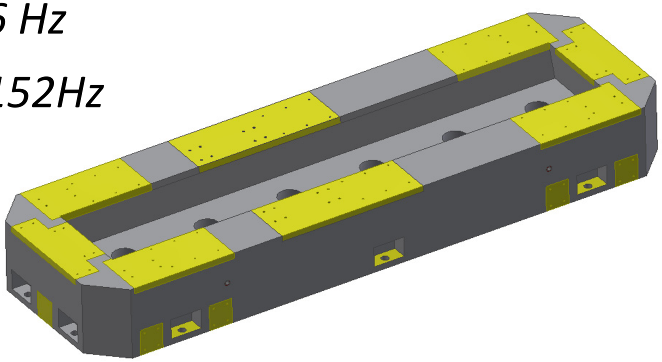
Design of Plinth

- *Design proposal*：
  - Reinforced concrete precast，
    - *good overall stiffness.*
    - *Elasticity modulus of concrete can be increased >50GPa*
  - grouting
    - *Seamless connection*
    - *improve the stiffness of the system*
  - prototype free BC test result：

    MP - 106 Hz

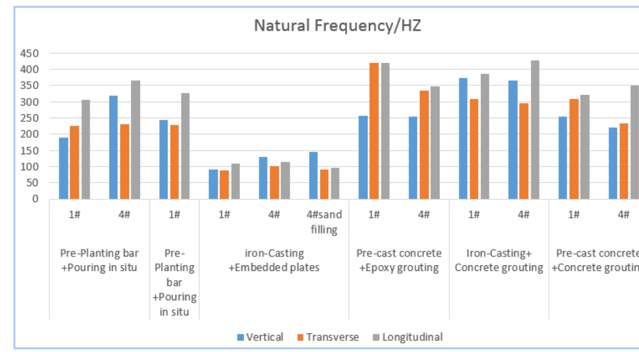
    FODO - 152Hz





Installation Process of Plinth*

- *The method of fixing the plinth is of vital importance in the stability of the support system*
- *Six different process were carried out, and the results are as follow:*
  - *Secondary grouting can effectively improve stability*
  - *epoxy-based grout is better than concrete-based performance*
  - *the construction process need to be complied with strictly.*

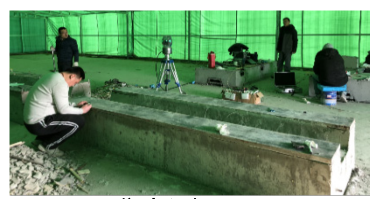


- *Epoxy secondary grouting program is determined.*

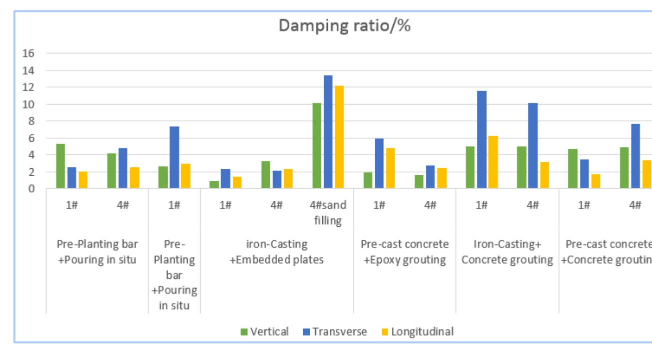
浇筑前地面凿毛

预制件浇筑

预埋板



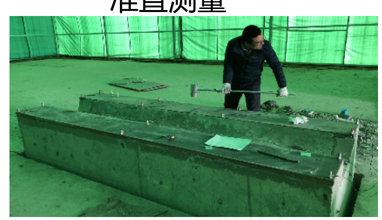
准直测量



21 铸件灌浆后

浇筑前界面冲洗

现场就位调平

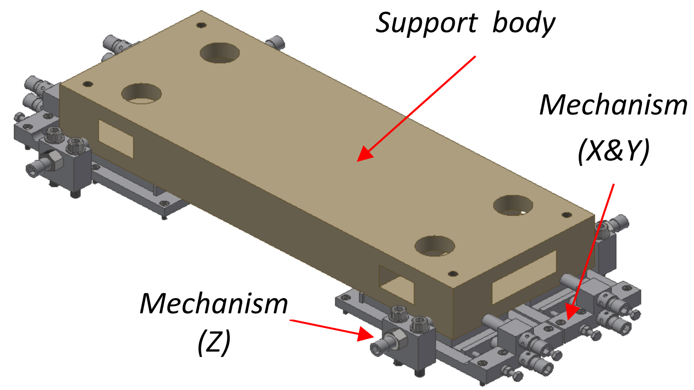


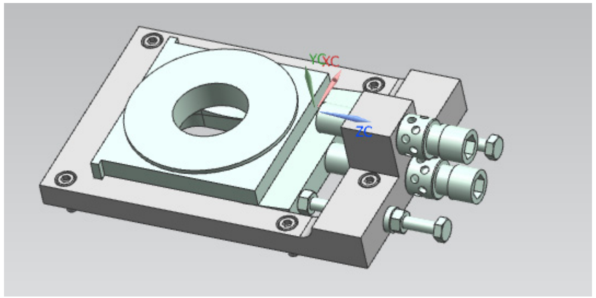
振动测试

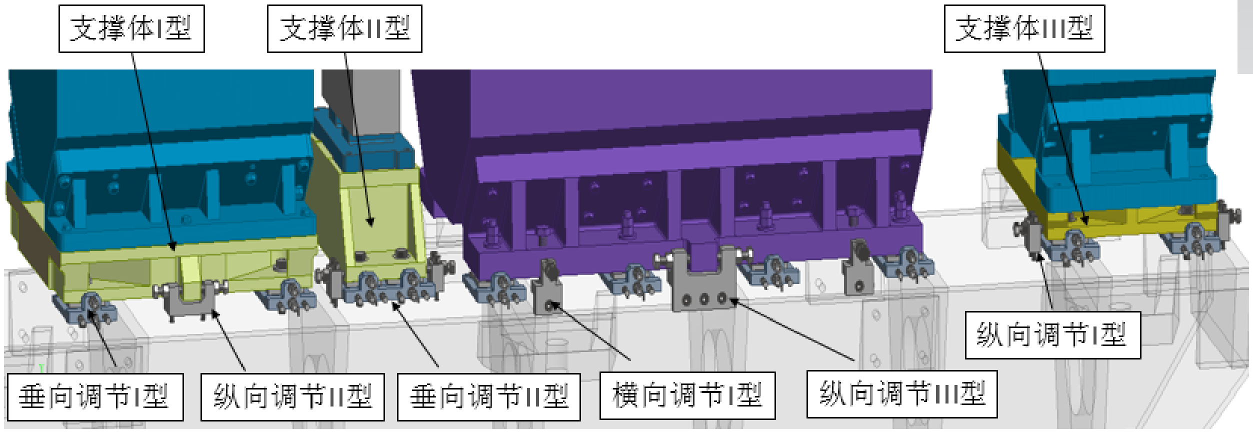
*:lichunhua et al.,Experimental study on magnet support plinths of advanced light source [J].High Power Laser and Particale Beams ,2021,33(03):82-87.

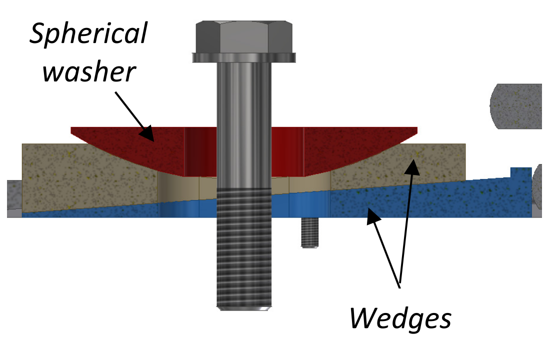
Magnet Alignment Mechanism

- *Requirement*： *Align the magnets on one girder precisely with the motion resolution of 1μm.*
- *Mechanical design*：
  - *Cast steel support body, good dimensional stability, easy to shape.*
  - *Vertical adjustment: Wedges with spherical, adjustable range of ±1mm*；
  - *Horizontal adjustment: Screws, ±4mm.*



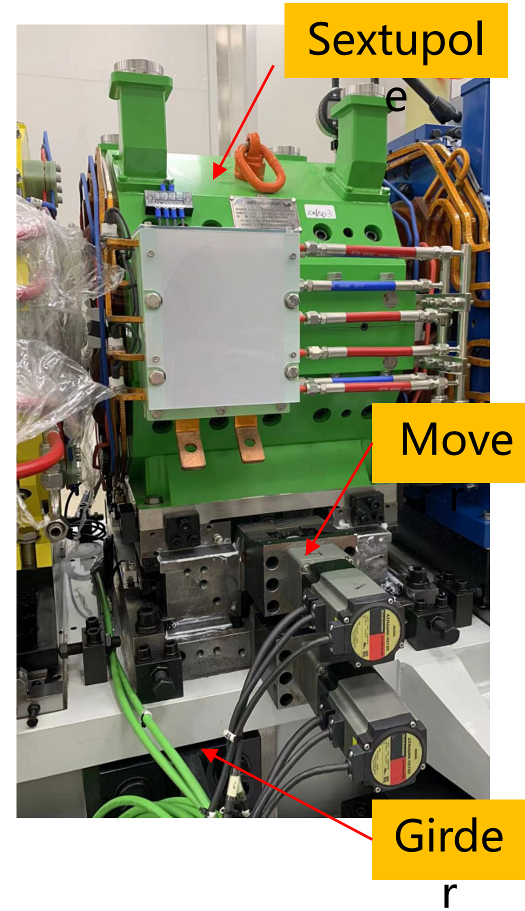


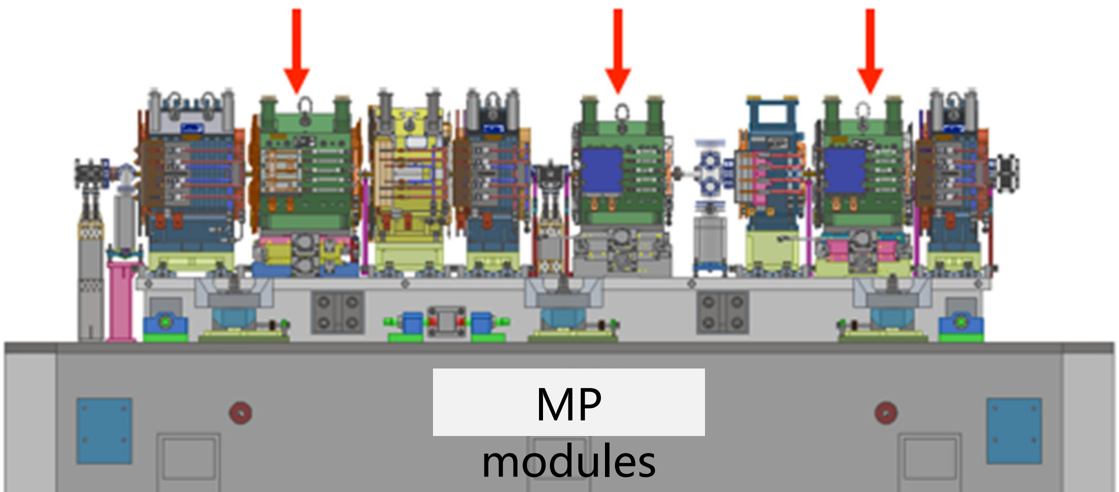




Magnet Alignment Mechanism - Mover

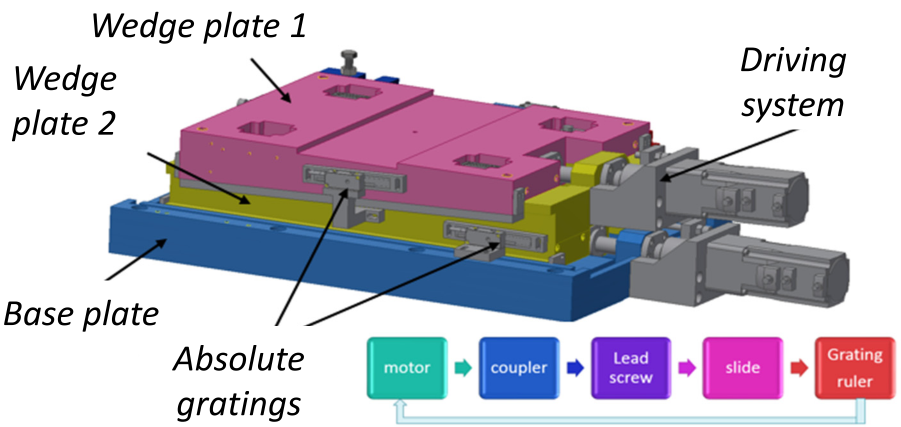
- *Remote Mover is proposed for the sextuple position adjustment online, and for optical parameters correction.*
  - *Located on the MP modules, 288 in total*
- *Physical requirements:*
  - *Transversal & vertical motion accuracy: 5μm, at the magnet center.*
  - *adjustable range online: ±0.3mm*
  - *No influence on the magnet support system stability.*





Magnet Alignment Mechanism - Mover

- *Difficulties:*
  - *high load-bearing capacity, Limited space,*
  - *High stiffness & motion accuracy*
- *Mechanical Design:*
  - *Wedge mechanism*
  - *Drive system: Ball-screw +Step motors*
  - *Absolute gratings for feedback*



Parameters		*Values*
Displacement errors	*X/Y*	*2μm*
Angular errors	*Pitch*	*2”*
	Yaw/roll	*3”*
Moving range		*±1mm*
1st natural frequency		*54Hz*
Load		*450kg*

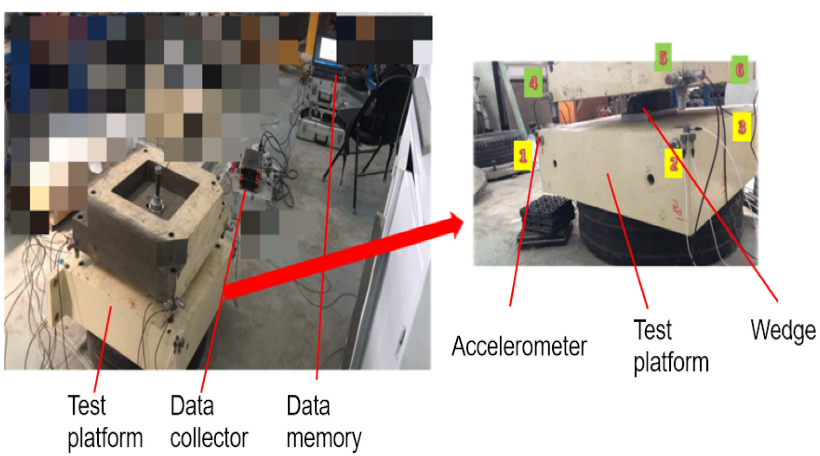
For detailed design, machining and experimental content, see article “Development and motion performance study of HEPS Mover” by Yang Shu

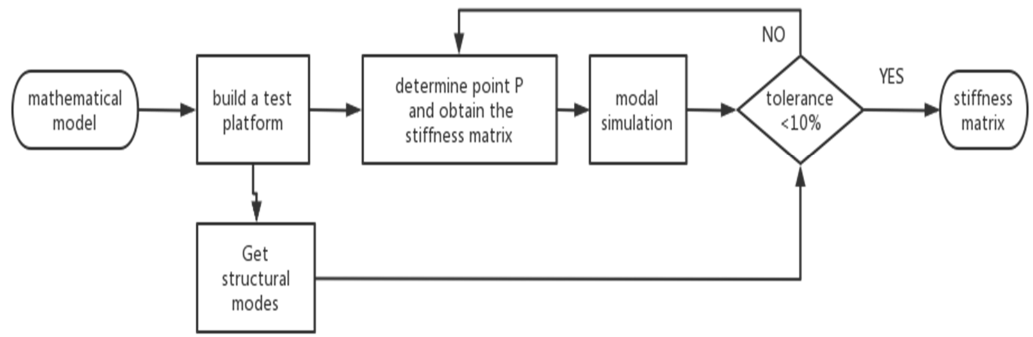
Modal Simulation Study

The stiffness of components has an important influence on the stability and simulation results of the support system

Purpose: Determine the stiffness to improve the accuracy of the simulation results

Method: rigid-body dynamics* → frequency response function (FRF) measurements → finite element analysis (FEA) simulation → accurate stiffness





$$\begin{bmatrix} m & 0 & 0 & 0 & mR_{cp\_z} & -mR_{cp\_y} \\ 0 & m & 0 & -mR_{cp\_z} & 0 & mR_{cp\_x} \\ 0 & 0 & m & mR_{cp\_y} & -mR_{cp\_x} & 0 \\ 0 & -mR_{cp\_z} & mR_{cp\_y} & I_{xx\_p} & 0 & 0 \\ mR_{cp\_z} & 0 & -mR_{cp\_x} & 0 & I_{yy\_p} & 0 \\ -mR_{cp\_y} & mR_{cp\_x} & 0 & 0 & 0 & I_{zz\_p} \end{bmatrix} \begin{bmatrix} \ddot{x}_p \\ \ddot{y}_p \\ \ddot{z}_p \\ \ddot{\theta}_x \\ \ddot{\theta}_y \\ \ddot{\theta}_z \end{bmatrix} = \begin{bmatrix} K_{xx} & & & & & \\ & K_{yy} & & & & \\ & & K_{zz} & & & \\ & & & K_{\theta_x\theta_x} & & \\ & & & & K_{\theta_y\theta_y} & \\ & & & & & K_{\theta_z\theta_z} \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ z_p \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}$$

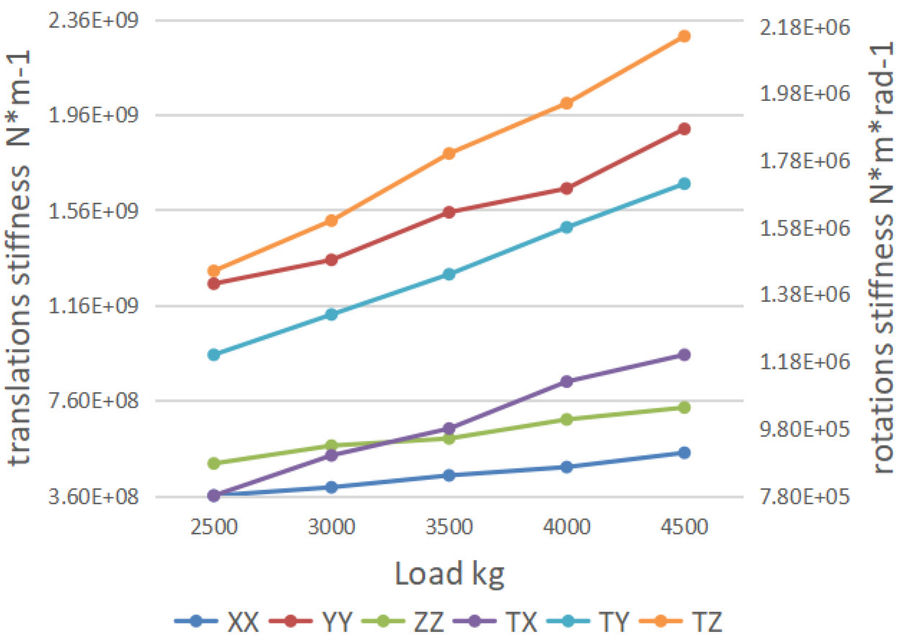
*:PATRICIA J. et al., “USING RIGID-BODY DYNAMICS TO MEASURE JOINT STIFFNESS ”, Mechanical Systems and Signal Processing (1999) 13(5), 789-801.

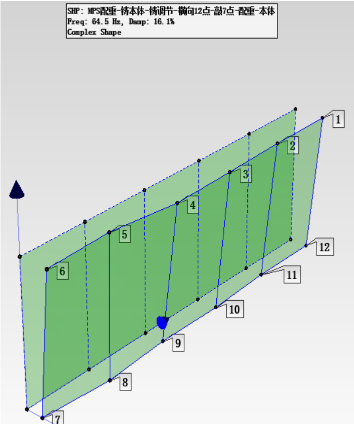
Modal Simulation Study

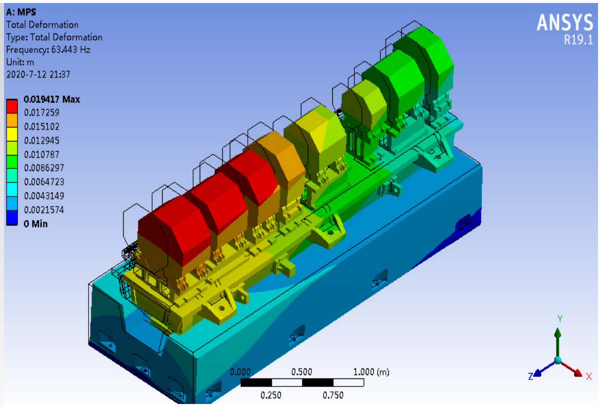
Achievements:

-The stiffness matrix of the adjusting mechanism was obtained

-Improved accuracy of support system simulation results, consistent with test results (error ＜10%).



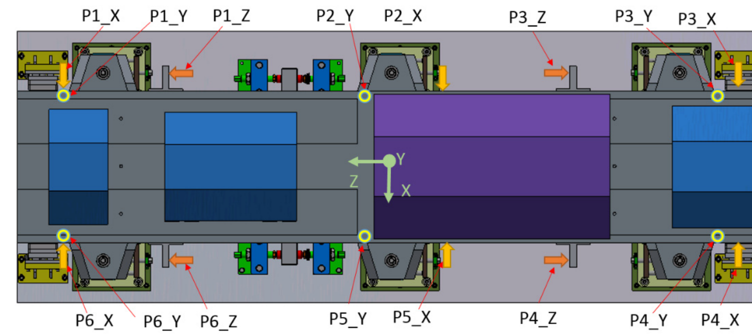


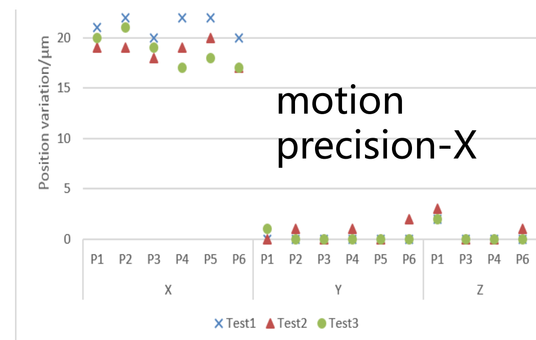


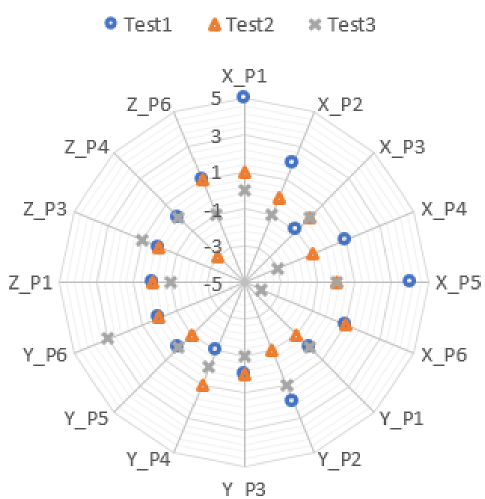
Order	1	2	3	4	5	6
Test /Hz	64.5	74	90.4	107	123	142
Simulate /Hz	63.4	70.6	82	107.7	124.4	137.4
Error	-2%	-5%	-9%	1%	1%	-3%

Motion Test of Prototye*

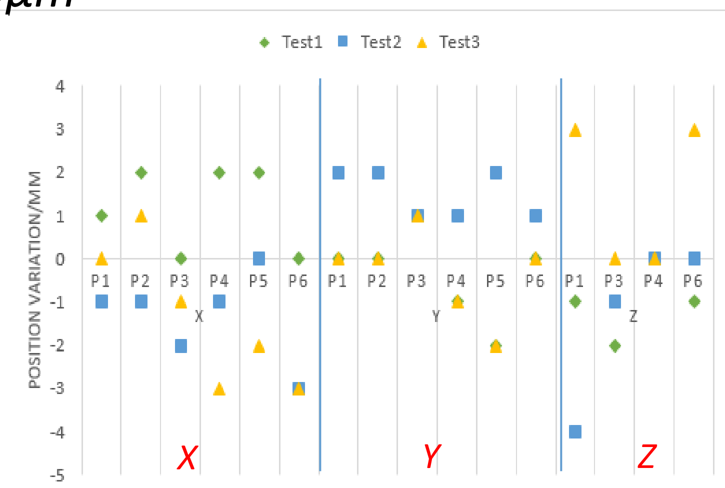
- Method: dial gauge
  - ✓Adjustment Resolution~ *1μm*
  - ✓Motion precision< *5μm*。
    - ✓ *motion coupling < 3μm*。
  - ✓Locked offset *<5μm*



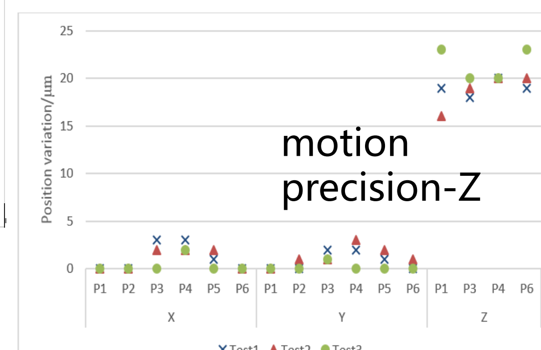




locked offset



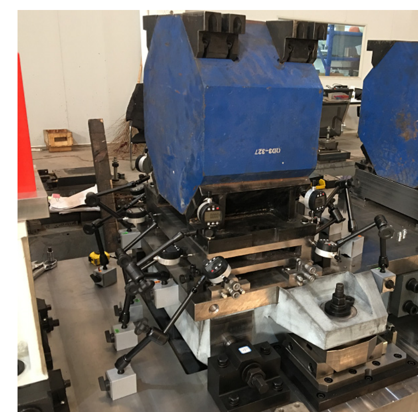
position variation



*:*Chunhua Li et al., "DESIGN AND TEST OF SUPPORT FOR HEPS MAGNETS", Radiation Detection Technology and Methods (2021) 5:95–101.*

Prototype Test*

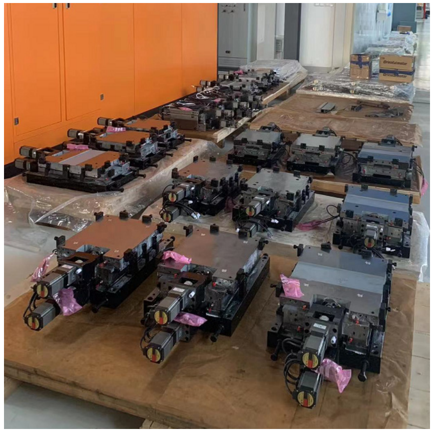
- *Support prototypes (half-arc section) were assembled for test.*
  - *MP, FODO, DQ, BLG*
  - *Motion performance and stability reach the requirements.*



:Chunhua Li et al., “DESIGN AND TEST OF SUPPORT FOR HEPS MAGNETS”, Radiation Detection Technology and Methods (2021) 5:95–101.

Batch Progress

- *Concrete plinth: Grouting in tunnel is completed and passed the final acceptance.*
- *Girder: Batch delivery finished and pre-alignment is close to complete.*
- *Mover: Arrival acceptance check is completed one by one.*
- *Tunnel installation is completed by 85% .*



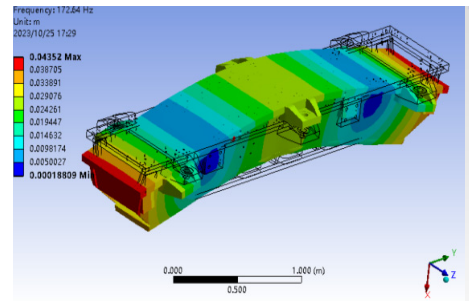
Batch Test

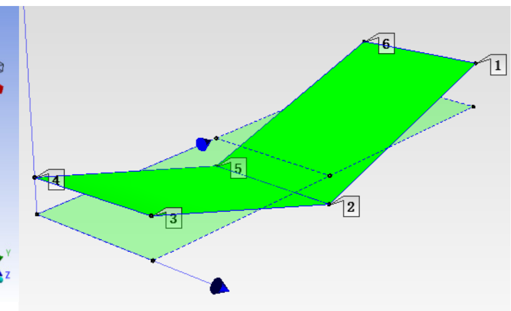
Free BC modal test in batch production

-Plinth≥135Hz, Girder≥161Hz

all of them fufill requrements

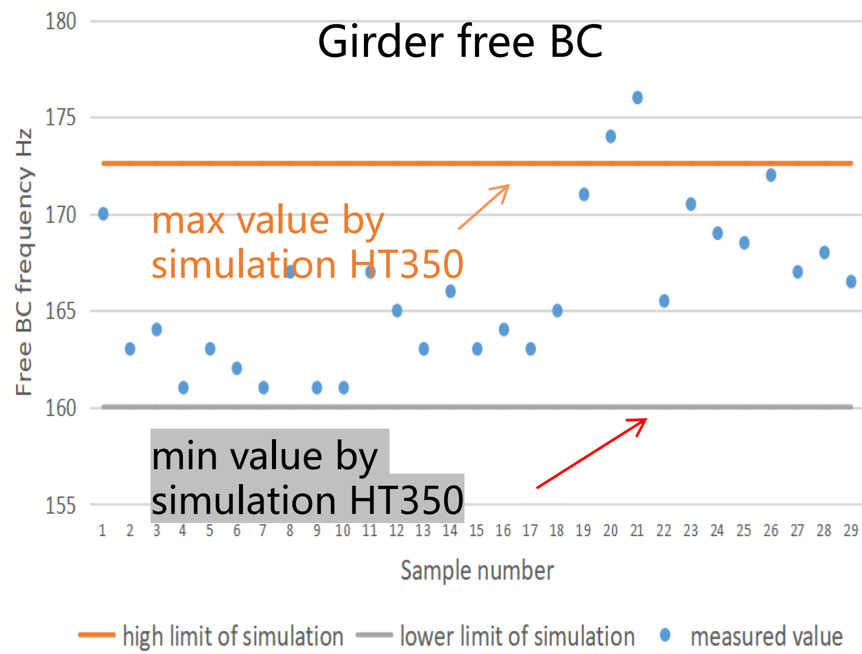
- Simulation and test results are consistent





Plinth free BC

Type	*number*	*Free BC frequency /Hz*	
		design value	*Measured min value*
MP	*96*	*≥120*	*135*
FODO	*96*	*≥150*	*166*
DQ	*96*	*≥590*	*599*

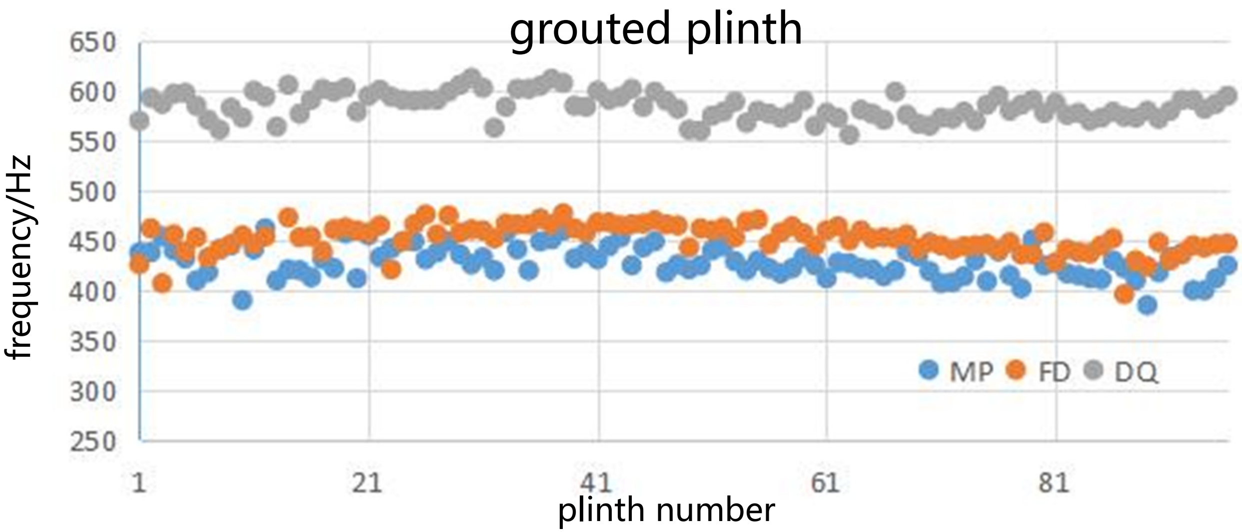


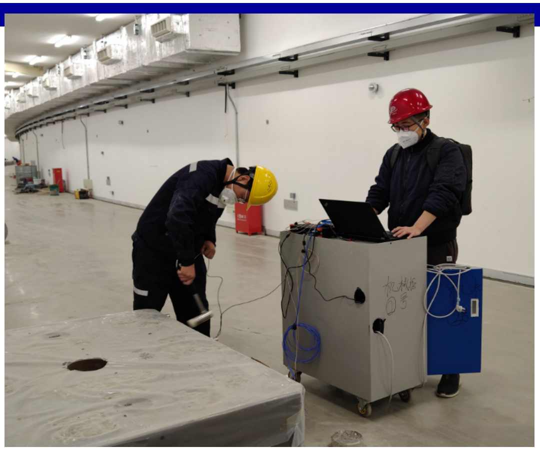
Batch Test

Fixed BC modal test in batch production

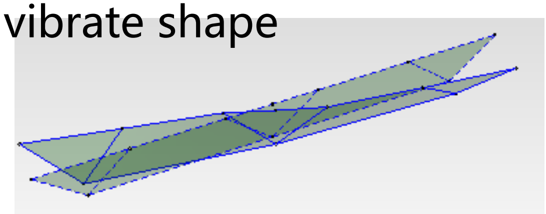
-Grouted plinth frequency＞250Hz,

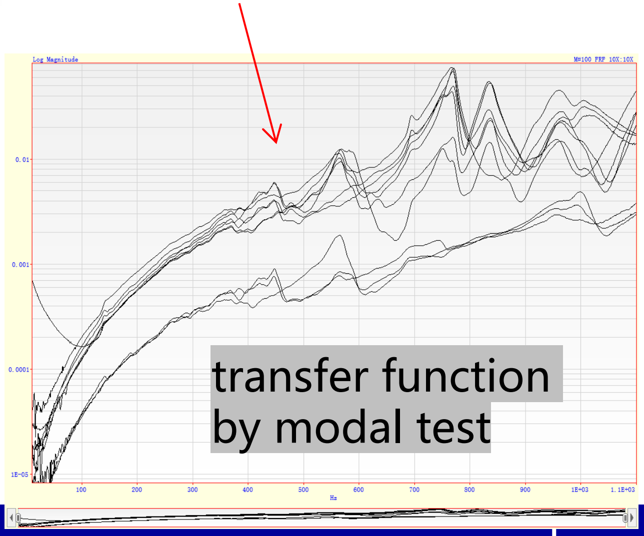
fufill requirement.





vibrate shape

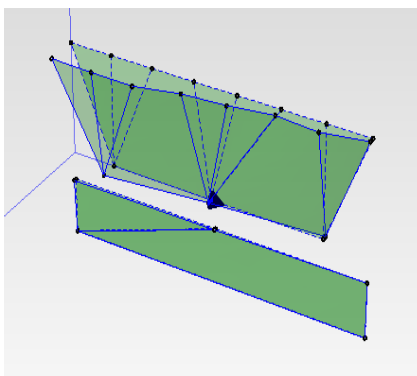


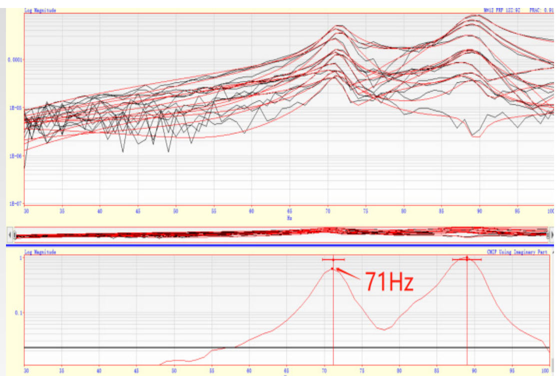


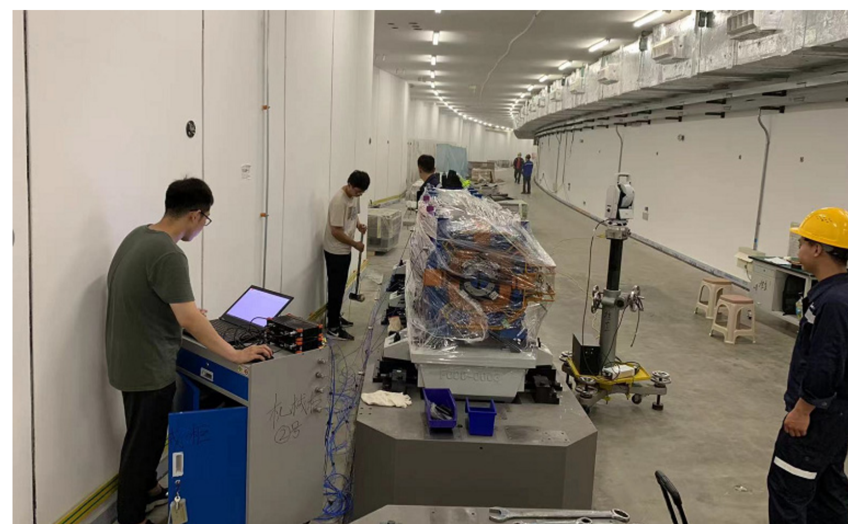
Type	*MP*	*FODO*	*DQ*
Measured mean value/Hz	*428*	*452*	*585*

Batch Test

- *Test the stability of the support system in tunnel*
  - *MP/FODO/DQ: 71Hz(minimum)*
- *all greater than the requirements*







Type	*number*	*mean value/Hz*	*max value/Hz*	*min value/Hz*
MP	*69/96*	*99.7 Hz*	*106 Hz*	*90 Hz*
FODO	*47/96*	*75.9 Hz*	*82 Hz*	*71 Hz*
DQ	*88/96*	*104.7 Hz*	*116 Hz*	*94 Hz*

Summary

- *General design of magnet support system is presented.*
- *The studies of the key process are accomplished.*
- *The performance of the system have reached the requirements.*
- *Key equipments have arrived in batch and tunnel installation is completed by 85% .*
- *The installation of the remaining equipments will be finished in next year.*

Thanks for your attention！