Design and alignment accuracy of HEPS magnet girder adjustment mechanism*

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Abstract

Very low emittance of High Energy Photon Source (HEPS) demands high stability and adjusting performance of the magnet support. The alignment error between girders should be less than 50 µm. Based on that, the adjusting resolution of the girder are required to be less than 5 µm in both transverse and vertical directions. To fulfill the requirements, during the development of the prototype, the structure was designed through topology optimization, static analysis, and the rationality of the structure was verified through prototype experiments. Based on the magnet alignment accuracy requirements, error distribution and control, the magnet locking running amount, magnet opening and closing running amount, girder transportation running amount, adjustment deviation and other aspects of a more in-depth experimental research.

I. INTRODUCTION

HEPS storage ring consists of 48 modified hybrid 7BA achromats. The circumference is 1360.4 m and each arc section is about 28 m. HEPS is designed with very low emittance of less than 60 pm.rad to provide much brighter synchrotron light. Precise positioning and stable supports of the magnets are required.

The alignment error between magnets on a girder should be less than 30 µm in horizontal and vertical direction, and that between girders should be less than 50 µm. Also, natural frequency of magnet support system should be higher than 54 Hz to decrease amplification of ground vibrations, which is very challenging. The requirements are listed in Table 1& Table 2[1].

Table1: Alignment Tolerance

Tolerances	**Magnet to Magnet**	**Girder to Girder**
Transverse	±0.03mm	±0.05mm
Vertical	±0.03mm	±0.05mm
Longitudinal	±0.15mm	±0.2mm
Pitch/yaw/roll	0.2mrad	0.1mrad

According to the layout of the magnets, there are 6 support units for the multipoles in each arc section, including 2 FODO modules, 2 MULTIPLET modules and 2 QDOUNLET modules, as shown in Fig.1. The adjacent multipoles share one girder and are seated on the plinths through adjustable wedge mechanisms, while the 5 longitudinal dipoles are bridged between the plinths.

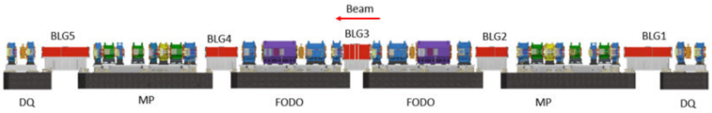


Fig.1 One arc section(1/48)

Stringent alignment accuracy requests high adjusting resolution of the girders. Table 2 shows the requirements. The resolution should be better than 5µm in transverse and vertical directions and 15 µm in longitudinal direction.

Table 2: Requirements for Support System

Parameter		Value
Resolution	Transverse	≤5µm
	Vertical	≤5µm
	Longitudinal	≤15µm
Natural frequency		≥54Hz

II. DESIGN OF THE SUPPORT SYSTEM

The support system is designed as Fig.2 shows. The girder should be capable of moving in 6 dimensions and the adjusting mechanisms are designed with 6 sets in vertical direction, 2 sets in transverse and 1 set in longitudinal direction. Each magnet is supported by a special adjusting mechanism to realize the three-direction adjustment, in which the sextupole is supported by the mover, which is able to realize the online adjustment.

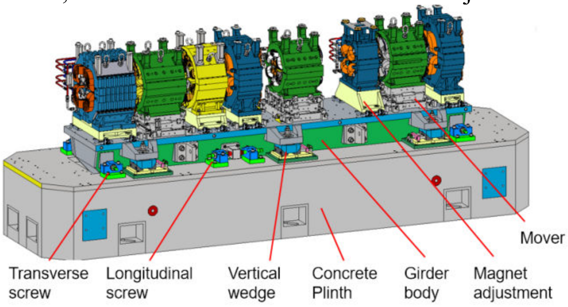


Fig.2 Support system

Girder Body

After pre-simulation optimization [2], the effects of different structural parameters of the girder body on its deformation and natural frequency are analyzed, and the optimal stiffness is obtained by optimizing the shape of the cross-section and the distribution of the stiffeners. The structure of the girder body is a six-point support box structure as shown in Fig.3, and the material is HT350, which has higher structural damping, less residual internal stress, and more stable long-term dimensions. Under the same load condition, the multi-point support method has more space for optimization of the girder body.

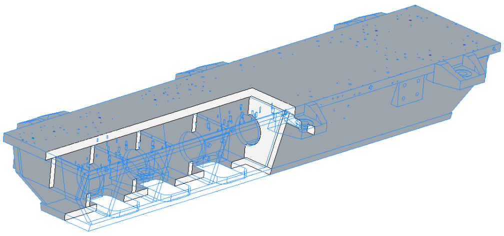


Fig.3 Girder body

Surface Flatness

The flatness of the girder prior to mounting magnets reflects machining accuracy. The alignment system surveyor measured the flatness of the unpainted surface of the girder surface using a multiplexed laser system (measuring accuracy better than 10 microns). Many points on the top surface of the 3.3m long girder were measured, as shown in Fig.4. Flatness of the girder is ±17 microns peak-peak.

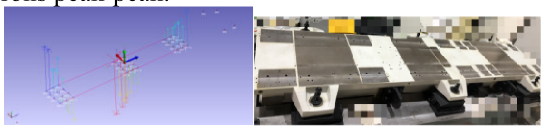


Fig.4 Measured flatness of girder body

Plinth

structural design

With the advantages of good stability and low cost, concrete plinth is adopted by many synchrotron accelerators [3, 4]. The normal Elastic modulus of concrete is about 30GPa, which is relative low to resist deformation. So high Elastic modulus recipe was developed and the sample achieved 53 GPa. The plinth is a reinforced concrete precast structure, which is designed to be groove shape to match the girder installation, as shown in Fig.5.

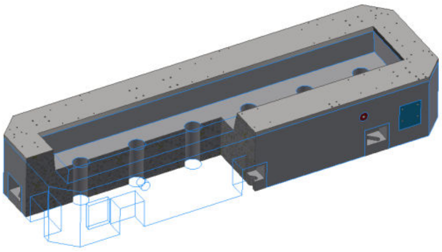


Fig.5 Plinth

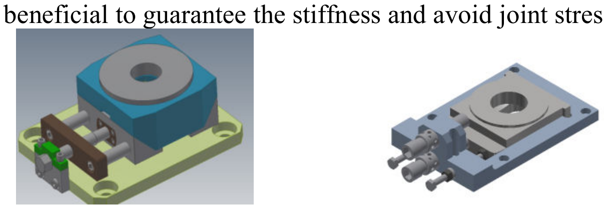
Displacement Test after grouting

Excessive displacement of the plinth after grouting, beyond the adjustment range of the support structure, can cause serious impacts on the beam track. There are many factors that affect the plinth displacement before and after grouting: adjustment error, alignment control network measurement error, foundation settlement, plinth movement during grouting and grout solidification. The alignment system surveyor used a laser tracker to record the position of each plinth before installation and after grouting, and the results were: (1) the maximum deviation of the horizontal was 3.5mm; (2) in the vertical direction, the deviation of 5 pedestals was >1mm, the maximum deviation was 2.14mm, and the rest were ＜1mm.

Support Components

Vertical

In order to fulfill the pre-alignment and stability requirements, the support system is hierarchical adjusted of girder and magnets. High stiffness wedges are used as mechanisms for supporting and vertical motion, as shown in Fig.6. The top surface of the wedge is equipped with a spherical disc to compensate for the angle change during alignment operation and keep contact of the interface. It is beneficial to guarantee the stiffness and avoid joint stress.



Girder body adjustment Magnet adjustment

Fig.6 Vertical adjustment

Sextupoles in the storage ring of HEPS will be adjusted based on beam trajectory. The mechanical design of a beam-based alignment sextupole mover should be developed. The motion accuracy of the mover should be better than 5 μm under 450 kg load of sextupoles. After preliminary prototype development, the structure of the mover was finalized as a 3-layer sliding wedge structure[5]. The movement range is required to be±0.3 mm in both horizontal direction and vertical direction.The yaw and roll should be less than 3”, and the pitch should be less than 2”. The horizontal displacement during vertical movement, which is called coupled error, should be less than 15μm.

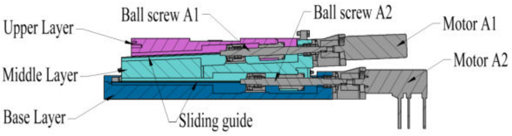


Fig.7 Mover

Horizontal

Horizontal adjustment includes transversal and longitudinal adjustment, and the focus of the mechanism design is to realize precise adjustment resolution. On the one hand, the movement mechanism itself should have the function of fine movement, on the other hand, the mechanism and its supporting structure are required to have high enough rigidity to avoid large deformation and “tampering” phenomenon when subjected to force.

Based on the available design space, the longitudinal adjustment mechanism of the girder is arranged in the middle of the girder, which is located between the two adjacent vertical pivot points, and the horizontal adjustment mechanism is located at both ends of the girder, and one set is arranged on each side of the girder considering the symmetry of the movement. The longitudinal adjustment mechanism adopts an ordinary screw push top mechanism, as shown in Fig. 8, where the screw applies thrust through the force member mounted on the support to realize the movement of the girder. Similar to the transveral mechanism, the design focuses on the rigidity of the support force members as well as the adjustment mechanism to improve the response sensitivity of the movement. In this case, the screw has a fine thread of M30 and the screw end is also designed with a universal ball head.

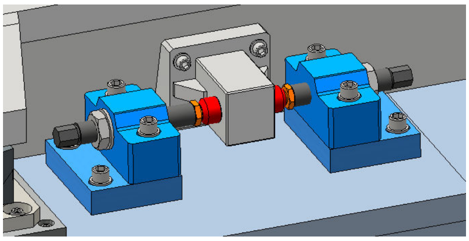


Fig.8 Horizontal adjustment mechanism model

III. ALIGNMENT ACCURACY STUDY OF THE SUPPORT SYSTEM

Based on the alignment accuracy requirements of the common girder magnets, the error allocation and control of the storage ring magnets are proposed as shown in the table below, in which the alignment accuracy requirements related to the support structure include: pre-alignment adjustment deviation, magnet locking running control, magnet opening/closing running control, magnet running control during transportation of pre-alignment girder, and tunnel adjustment deviation control, for which an in-depth study of the relevant important links is required.

Table 3: Magnet alignment accuracy analysis

Final Accuracy		**Stage Accuracy**		**Fundamental accuracy**	
Total	0.047	Pre-alignment	0.029	Magnetic center of magnet leads to calibration accuracy	0.01
				measurement error	0.01
				adjustment deviation	0.015
				magnet lock	0.01
				Magnet open and close	0.01
				transport	0.015
		Tunnel alignment	0.036	Adjustment of displacement measurement accuracy	0.005
				adjustment deviation	0.02
				Relative control measurement accuracy	0.03

Motion performance test of prototype

（1）Adjustment resolution and motion accuracy test

The adjustment deviation is mainly determined by the resolution and motion accuracy of the adjustment mechanism. As shown in Fig.9, two dial gauges are fixed at each support points of the girder to monitor transverse (X), vertical (Y) and longitudinal(Z) offset. The dial gauges reading show that the girder can be operated by 1μm per step in all three directions.

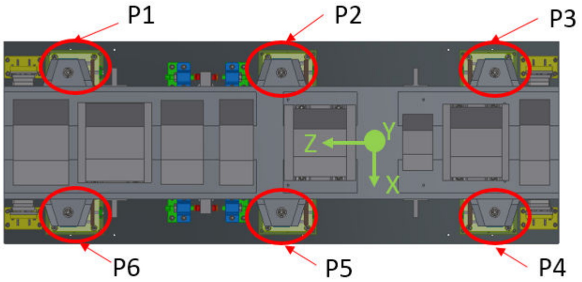


Fig.9 schematic diagram of measuring point

The motion precision of the girder is largely determined by the coupling of the motion. In the actual alignment process, the vertical position is adjusted firstly, the coupling amount can be compensated in the subsequent horizontal adjustment. Therefore, the test mainly focuses on the motion coupling in horizontal adjustment.

In the test, 20μm was used as the motion step, and the change of the dial gauges reading is recorded. The moving precision results are shown in Fig.10. It can be seen that the moving errors of each measurement point in 3 directions are all less than 5μm.

The motion coupling result in horizontal adjustment is shown in Fig.11 to 12, and the position variation is less than 3μm.

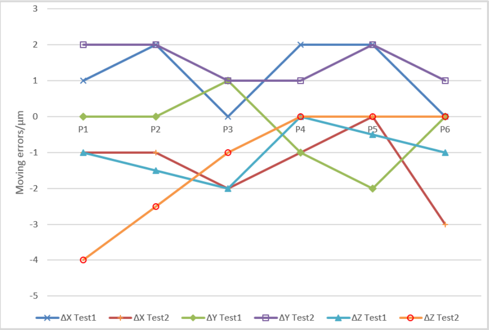


Fig.10 Motion precision test result

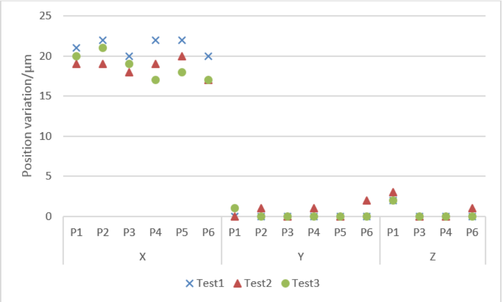


Fig11 Position variation in transverse motion

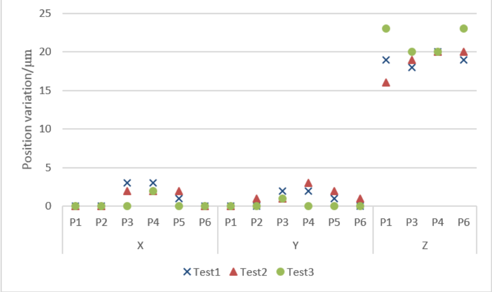


Fig.12 Position variation in longitudinal motion

（2）Locking Test

To ensure long-term position stability and connection stiffness, locking is necessary. The clearance between the support surfaces will be eliminated after tightening and the settlement is inevitable. Meanwhile the horizontal position of the girder varies in a certain degree. In order to minimize the offset, the tighten-tune cycling process is used in the test. The settlement is compensated in time by the tuning-up of the vertical wedges. By this way, the girder can be fixed in position, and the offset in three directions can be controlled within 5um, as shown in Fig.13.

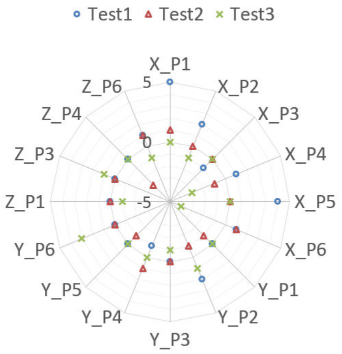


Fig.13 Test results of locking offset

Magnet opening and closing repeatability test

Due to the limitation of vacuum box processing time, the vacuum box needs to be installed after the magnet pre-alignment is completed, therefore, the magnet position after the upper core opening and closing needs to be able to meet the pre-alignment accuracy requirements. The error matching process requires the magnet opening and closing repeatability to be better than 0.01mm, and the experimental object is the standard MP and FODO type pre-alignment girder. The pin is the key structure of magnet repetitive positioning. The dismantled upper core needs to be placed on an absolutely smooth supporting platform, e.g. a marble platform. Storage time after removal > 48h.

Fig.14 Magnet opening and closing repeatability test

The experimental process using a multiplex laser system, measure and record the magnet position before removal and after installation, the results are shown in the table below: before and after the opening and closing of the magnet position change <0.01mm, and the theoretical value of the deviation are <0.02mm, to meet the error requirements. Analyze the reasons for the error: The main contribution is the change in position of the ABF and BD magnet, most likely due to stress relief from magnet disassembly, with iron chipping residue in the BD magnet pin position.

Therefore, in the bulk installation process should ensure: (1) disassembly and assembly parts stowage; (2) open and close the magnet tightening bolt order and torque requirements; (3) magnet open and close before and after, the pin position remains unchanged, the angle as far as possible to restore。

Table 4: Magnet opening and closing test results

Type	**standard deviation/mm**		
	DX	**DY**	**DZ**
MP	0.006	0.008	0.005
FODO	0.006	0.003	0.004
	0.006	0.003	0.004

Girder Transportation Reliability Test

After completing the pre-alignment, the magnet girder needs to be transported to the HEPS tunnel for installation, via the sinking channel, and the magnet position after transportation needs to meet the pre-alignment accuracy requirements. Based on the principle of error distribution, the magnet movement before and after the transportation of the pre-alignment girder should be controlled within 0.015mm. The experimental objects are the standard girder MP type and FODO type, and the route is from the pre-alignment thermostat room to the tunnel installation hall. In order to ensure the stability of the transportation process, the self-leveling vibration damping transportation platform is adopted, the speed of the transportation vehicle is controlled at 10-20km/h, and the six support points of the girder are kept balanced during transportation.

Fig.15 Girder Transportation Reliability Test

Before and after the transportation are used multiplexed laser system, measurement and recording of each magnet position, the results are shown in the table below: girder before and after the transportation of the magnet XY position change <0.010, and theoretical value deviation are <0.015, to meet the error requirements.

Table 5: Girder Transportation Reliability Test results

Type	**standard deviation/mm**		
	DX	**DY**	**DZ**
MP	0.005	0.004	0.005
FODO	0.006	0.006	0.010

IV. CONCLUSION

The requirements of HEPS storage ring magnet support are very challenging. The girder body and magnet hierarchical adjustment structure provides structural support for the realization of alignment accuracy, and high stiffness with micron-level adjustment accuracy is a key concern of the structural design process.The secondary grouting plinth, cast iron girder and wedge-type adjusting mechanism well solve the above needs. Through the motion performance test of the prototype, the adjustment performance of the structure is verified: the adjustment resolution is better than 1 micron, the motion accuracy is better than 5 microns, and the locking runnning amount is better than 5 microns. The magnet opening and closing repeatability experiment verifies that the magnet position change before and after opening and closing is better than 10 microns; the girder transportation experiment verifies that the magnet position change before and after transportation is better than 10 microns. The above research lays a solid foundation for the realization of tunnel magnet alignment accuracy.

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