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Mechanical design and performance evaluation of KB mirror system for the ARPES beamline at SSRF



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ARTICLE INFO

Article history: Received 1 November 2015 Received in revised form 18 February 2016 Accepted 18 April 2016 Available online 21 April 2016

Keywords: Synchrotron radiation Mechanical design Precision device KB mirrors Numerical simulation

ABSTRACT

A new angle resolved photoelectron energy spectrum (ARPES) beamline is designed as a branch of the photoelectron experimental system (dreamline) at Shanghai Synchrotron Radiation Facility (SSRF). Its purpose is to provide a powerful instrument to conduct ARPES experiments for users from all over the world. During the design and construction of the beamline, many technical difficulties needed to be solved because of its high energy resolution, high photon flux and high focusing quality, including the design of monochromator, the design of Kirkpatrick–Baez (KB) mirror system and the manufacture of the optics. In this paper, the KB mirror system is described, including its principle and design scheme. The practical significance of displacement function is discussed. For vertical linear driving mechanism, the variation of resolution and repeatability induced by its axial deformation and radial deformation is analyzed. The results show that it is within the scope of permissible error. Linear resolution and repeatability, and angle resolution and repeatability are tested as $0.56 \,\mu$ m, $1.6 \,\mu$ m, 0.6'' and 1.08'', which guarantee the high accurate motion of KB mirrors and further improve the performance of the beamline. The simulation and ray tracing results of the beamline show that the energy resolution is better than $11.2 \,\mu$ m (FWHM), demonstrating that the performance is beyond prediction.

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1. Introduction

The photoelectron experimental system (dream line) is a scientific instrument supported by national major research project of China. The mission of this soft X-ray beamline is to provide wide-wavelength range (20–200 eV, 200–2000 eV) and ultra-high resolution (25 meV @ 1000 eV). The beamline has two experimental stations: the angle-resolution photoelectron energy spectrum (ARPES) station and the photoemission electron microscopy (PEEM) station.

ARPES is an important technology to study electronic structure at crystal surface, such as energy band, Fermi surface and multibody interactions. Its history can be traced back to 1887 when Hertz discovered the photoelectric effect (Feuerbacher et al., 1978; Kevan, 1992). With the improvement of ultra high vacuum technology, electronic detection technology and photoemission theory, ARPES is now an important experimental method that attracts

the attention of many researchers (Azoulay, 1983; Leveque et al., 1991; Takayuki et al., 2011). Synchrotron radiation is the preferred source for ARPES experiments and enables new experiments because of its high brightness, collimation, coherence, polarization and wide wavelength. Therefore, the synchrotron radiation facilities all over the world are building ARPES beamlines. The successful construction of the dreamline at Shanghai Synchrotron Radiation Facility (SSRF) will make it one of the most advanced optoelectronic experimental systems in the world. Fig. 1 is a layout of the dreamline. A white light slit at 20 m from the elliptically polarized undulator (EPU, insertion device) determines the acceptance angle of the beamline, and absorbs most of the source heat load. At 22 m, a deflecting mirror, whose function is to absorb the heat load and to suppress the high-order harmonics, deflects the beam in the horizontal direction with the incidence of 1.2°. At 27 m, there is a variable-included-angle variable-line-spacing plane-grating monochromator equipped with four gratings including a low energy grating, a middle energy grating, a high energy grating and a very high energy grating. Each grating is optimized for a particular energy resolution and specific energy range. In order to share one EPU source, a switching mirror at 29.59 m is adopted to deflect the light at 2.5° to the PEEM station. At 45 m, there are

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Fig. 1. Layout of the dreamline. It includes ARPES and PEEM stations that share an EPU and a four-grating monochromator.

two monochromatic light slits for both ARPES and PEEM stations. After the monochromatic light slits, there are two sets of KB mirror system for ARPES and PEEM stations to focus the beam on the samples.

To realize the ultra-high resolution and wide-wavelength range, stringent requirements are proposed on almost all dreamline components. In the beamline, the double EPU (low-energy insertion device and high-energy insertion device) is employed to avoid high thermal load in the low-energy band. Internal water cooling of components is adopted to minimize thermal deformation. A variedline-space grating and a thermal correction system are used to correct the thermal deformation and improve the resolution. Invar alloy with the ability to minimize the thermal expansion coefficient is used for the frame to support the monochromatic light slit. KB mirrors are adopted to make the monochromatic light focus on the sample and to obtain a small light spot of a few microns. Due to the importance of the KB mirror system, many synchrotron radiation facilities and research institutes study these components. Recently, Naulleau et al. (2002) have studied an in-situ scanning slit system with KB mirrors, Matsuyama et al. (2010) have simulated an advanced four-mirror focusing system with KB mirrors, Ice et al. (2005, 2006) have studied thermal neutron KB micro-focusing optical elements and high performance KB super mirrors, Rau and Liu (2007) have studied a KB mirror system which can make the focus dimension of cone-shaped beam be less than 100 nm. In China, the group lead by Wang Zhanshan has extensively studied the optics, imaging quality, resolution and reflectivity of X-ray KB microscopic imaging systems (Mu et al., 2008; Ningning et al., 2006).

A KB mirror system is the key component for the dreamline, and its performance has a direct impact on the performance of the beamline. SSRF can supply a source with high photon flux, high spectral resolution and high spatial resolution. To maintain the advantages of the high brightness source, it is necessary to use KB mirrors with appropriate quality. Besides surface accuracy and manufacturing quality, the alignment and positioning of KB mirrors are critical to obtain a high quality focal spot. This puts strict requirements on the design, manufacturing, installation and debugging of the KB mirror system. This article will focus on the research of the ARPES KB mirror system for the dreamline. It will propose a reasonable design scheme, study the key structure, and test its performance. Finally, an evaluation of ARPES beamline will be presented. The purpose of this effort is ultimately to provide an outstanding photoelectron experimental system.

2. Principle of the KB mirror system

Kirkpatrick and Baez pioneered an X-ray microscope in 1948. Their design is composed of two orthogonal cylindrical or spherical reflectors (Naulleau et al., 2002). X-rays emitted from the source shoots the first mirror in grazing incidence, then are reflected by the second mirror, and finally focus to form an image. If the distance between the source and the center of reflector is p, and the distance between the center of reflector and the image surface is q, they will fulfill the equation (Mu et al., 2008):

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R\sin\theta} \tag{1}$$

Here, *R* is the curvature radius of the reflector, θ is the grazing incidence angle. Serious astigmatism will exist when the grazing incidence imaging is implemented by a single spherical or cylindrical mirror, because the beam focuses only in one direction, and does not focus in the other direction. In order to improve the imaging quality, two orthogonal reflectors are adopted to focus the beam. On the assumption that the two reflectors of the KB system have the same curvature radius, when the beam is emitted by the source A, then is reflected by the two mirrors M and N, and finally is focused on the image surface B, as shown in Fig. 2, the process of beam transmission will accord to the imaging equations:

$$\frac{1}{p} + \frac{1}{k+q} = \frac{2}{R\sin\theta_1}$$
(2)

$$\frac{1}{p+k} + \frac{1}{q} = \frac{2}{R\sin\theta_2}$$
(3)

where θ_1 and θ_2 are the grazing incidence angles of the two reflectors, *R* is the curvature radius.

KB mirror system is often applied in the field of synchrotron radiation science as a micro focusing device. It has the characteristics of high transfer efficiency (>70%), no dispersion, radiation resistance, and small aberration (Ming et al., 2011). When the KB mirror system is applied to realize micro focusing, it requires a large magnification, and the incident angle is limited below the angle of total reflection. In order to obtain good imaging with high flux, a long reflecting mirror with an ideal elliptical shape is adopted. Therefore, two elliptical mirrors are employed to construct the KB mirrors system in dreamline. When the object distance p, image distance q, and grazing incidence angle θ on the mirror center are known, the mirror center is taken as the origin of coordinate, the length direction of the mirror is taken as the X-axis, and the direc-



Fig. 2. Principle of the KB mirror system. It is composed of two orthogonal reflectors, and is applied to realize micro focusing.



(b) Three-point stage

Fig. 3. Structure of the alignment mechanism. (a) Shows that the alignment mechanism is composed of three vertical actuators, two horizontal actuators and two threepoint stages, it can realize five degrees of freedom of the reflector. (b) Shows that the three-point stage includes a ball-conic contact, a ball-V-section trench contact and a ball-hardened plane contact.

tion perpendicular to the mirror surface is taken as the Y-axis, the ideal elliptic equation can be obtained as follow:

3. Design of the KB mirror system

ellipse
$$(p, q, \theta, x) = \frac{(p+q)(p-q)x\cos\theta + 2\left(-pq + \sqrt{pq\left(pq - x^2 - px\cos\theta + qx\cos\theta\right)}\right)\sin\theta}{-(p+q)^2 + (p-q)^2\sin^2\theta}$$
(4)

Through this equation, we can get an elliptical cylinder by the bending method, or by direct processing method. In the dreamline, the two elliptical mirrors are processed directly; their slope errors and surface roughness are less than $5 \,\mu$ rad and $0.3 \,\mathrm{nm}$ respectively, reaching a high processing accuracy.

Good manufacturing accuracy and low surface roughness do not guarantee high performance of the KB mirror system. Only with the combination of a reasonable mechanical structure and precision adjusting mechanism can the KB mirror system achieve its potential performance. The ARPES KB mirror system of the dreamline is a high precision optical device integrating optical, precision mechanical, automatic control and ultra-high vacuum technologies. Its purpose is to focus monochromatic X-ray over a wide wavelength range. The main parameters of KB mirrors are shown in Table 1. For the KB mirror system, in addition to the two high accuracy elliptical reflectors, the position and rotation adjusting mechanisms are critical. Each mirror needs five independently degrees of freedom, and the distance between the two mirrors is very close, so some additional restric-



Fig. 4. Adjusting principle of KB mirrors. Y, Z, Roll, Yaw, and Pitch motions can be realized by the principle.

Table 1Parameters of KB mirrors.

	Mirror 1	Mirror 2
Figure	Elliptical cylinde	r Elliptical cylinder
Material	Si	Si
Grazing incidence angle (deg)	1.5	1.25
Object distance (m)	46.2	1.7
Image distance (m)	1.5	1
Semi-major axis (m)	$23.85\pm2\%$	$1.35\pm2\%$
Semi-minor axis (m)	$0.218\pm2\%$	$0.0284\pm2\%$
Dimensions (mm)	$500\times 30\times 40$	$150\times 40\times 50$
Coating	Au	Au
Meridian/sagittal slope error (µrad) (RMS) 2/5	0.8/5
Roughness (RMS)	0.3 nm	0.3 nm

tions are placed on the design scheme. In this article, the adjusting mechanism of the KB mirror system is described that combines an adjusting mechanism inside the vacuum and a feed-in mechanism outside the vacuum.

For the KB mirror system of the dreamline, the key problem is how to realize high rotation accuracy, high displacement accuracy and high repeatability. According to the performance requirements of the dreamline, the displacement resolution of the two mirrors should be less than 1 µm, and the displacement repeatability of the two mirrors should be less than 5 μ m. The requirements of the angle resolution of the first mirror are as follow: Roll angle resolution and Pitch angle resolution should be less than 1", and the Yaw angle resolution should be less than 0.8". The requirements of the angle resolution of the second mirror are as follow: Roll angle resolution and Yaw angle resolution should be less than 1", and the Pitch angle resolution should be less than 0.8". The angle repeatability of the two mirrors should be less than 5". The Roll direction means that the mirror rotates along the beamline direction, the Yaw direction means that the mirror rotates along vertical direction, and the Pitch direction means that the mirror rotates along the direction that is perpendicular to beamline direction and vertical direction. The Roll, Yaw and Pitch are shown in Fig. 2. Yaw motion affects the grazing incidence angle of first mirror. Pitch motion affects the grazing incidence angle of second mirror.

3.1. Design of the alignment mechanism

It is necessary to adjust the alignment of KB mirrors accurately to obtain near ideal focusing. Displacement of the mirror along beam direction is adjusted by the foot screws in the bottom of the device, and it is unnecessary to be adjusted accurately. Therefore, a precision alignment mechanism is needed to adjust the five degrees of freedom, namely *Y*, *Z*, Roll, Yaw and Pitch.

There are two traditional schemes, series adjusting scheme and parallel adjusting scheme, to realize the five-dimensional adjusting. For the series adjusting scheme, each degree of freedom needs an adjusting stage, and then these adjusting stages are stacked together. This scheme is feasible in theory, but its structure is not compact; it is very difficult to design and install the series adjusting mechanism in a limited space. For the parallel adjusting scheme, it is usually to adopt commercial six-bar parallel mechanism, which can realize the six-dimensional adjusting, but its cost is high, and its resolution, repeatability and other capabilities cannot reach the requirements of the KB mirrors. Therefore, a high performance five-dimensional alignment mechanism is self-developed; it is composed of three vertical linear actuators, two horizontal linear actuators, two three-point stages and precision linear guides, as shown in Fig. 3. The three vertical linear actuators can realize the adjustment of Y, Roll, and Pitch directions, and the two horizontal linear actuators can realize the adjustment of Z and Yaw directions. The three-point stage is based on a ball to conic contact, a ball to V-section trench contact and a ball to hardened plane contact.

There are two elliptical mirrors for this KB mirror system. The beam shoots the first mirror in a grazing incidence angle 1.5° in horizontal plane, and then the reflected beam shoots the second mirror in a grazing incidence angle 1.25° in vertical plane, and then focus on an exit slit. For the first mirror, the Yaw motion needs high accuracy to position it in a grazing incidence angle 1.5°. If the 1.5° cannot be guaranteed, or there is a large deviation between actual grazing incidence angle and theoretical grazing incidence angle, the reflected beam will deviate from its usual route and the focusing quality of the beam will be influenced. The Roll motion of the first mirror needs high accuracy, because it determines the orthogonality of the two mirrors that is related to the focusing quality of the beam. The Z motion of first mirror needs high accuracy, because the Yaw motion is realized by it, and if there is still any position error, it can be corrected by the Z motion. Comparing with other motions of first mirror, the Pitch motion and Y motion need relatively low accuracy, because they have little to do with focusing quality and the reflection of beam.

The similar situation exists for the second mirror. Pitch motion is related to the grazing incidence angle of second mirror, Roll motion is related to the orthogonality of the two mirrors, *Y* motion determines the realization of the Pitch motion, so Pitch, Roll, and *Y* motions need high accuracy. Yaw motion and *Z* motion have little to do with focusing quality and the reflection of beam, so they need relatively low accuracy comparing with other motions of second mirror.

The two mirrors are installed on two same alignment mechanisms respectively, so the alignment mechanism is designed according to the high accuracy requirements of motions of the two mirrors.

In order to improve the resolution and repeatability of the alignment mechanism, a high accuracy encoder is adopted to monitor



Fig. 5. Displacement functions of vertical linear actuators. If the values of Roll, Pitch and *Y* are known, the displacements *a*, *b* and *c* of three vertical linear actuators can be calculated through these functions. All the information from the displacement functions can be applied to improve the performance of alignment mechanism.



Fig. 6. Structure of the ARPES KB mirror system. It is operated in the 10⁻¹⁰ Torr vacuum, and the KB mirrors are equipped with a cooling device.



Fig. 7. Schematic diagram of force state of vertical linear actuator. It is in a quasistatic state, so *G* is in balance with the F_1 , F_2 and F_3 .

the displacement of the linear actuator. Fig. 4 is the schematic diagram of the five-dimensional adjusting system. In Fig. 4(a), A, B and C represent the three vertical linear actuators; the distance between A and D is *m* (actually 240 mm); the distance between B and C is *n* (actually 220 mm); \triangle ABC is an isosceles triangle. The Y motion, Roll motion and Pitch motion are controlled by adjusting the displacements of A, B and C linear actuators. In Fig. 4(b), E and F represent the two horizontal linear actuators, and the distance between two guides is *m* (actually 240 mm). The *Z* motion and Yaw motion are controlled by E and F linear actuators.

The alignment of the mirror is determined by the values of Roll, Pitch, *Y*, Yaw and *Z*, and can be fine-adjusted by changing the values of these physical quantities. In order to facilitate the control program, the unit of displacement is set to micrometer, and the unit of angle is set to arc-second. When the three vertical linear actuators are at the zero position, the initial values of Roll angle, Pitch angle and vertical displacement are supposed to be Roll₀, Pitch₀ and *Y*₀. When the two horizontal linear actuators are at the zero positions, the Yaw angle and horizontal displacement are supposed to be Yaw₀ and *Z*₀. In this state, assuming that the displacements of A, B and C linear actuators are *a*, *b* and *c*, and the displacements of E



Fig. 8. Schematic diagram of force state in limit position In this position, Pitch angle is 2° , and Roll angle is 0° .

and F linear actuators are *e* and *f*, so the expressions of five degrees of freedom are obtained as:

$$\operatorname{Roll} = \frac{180 \times 3600}{\pi} \arctan \frac{b-c}{n} + \operatorname{Roll}_0$$
(5)

$$Pitch = \frac{180 \times 3600}{\pi} \arctan \frac{b+c-2a}{2n} + Pitch_0$$
(6)

$$Y = \frac{2a+b+c}{4} + Y_0$$
(7)

$$Yaw = \frac{180 \times 3600}{\pi} \arctan \frac{e - f}{m} + Yaw_0$$
(8)

$$Z = \frac{e+f}{2} + Z_0 \tag{9}$$

When the physical quantities of Roll, Pitch, Y, Yaw and Z are known, the displacements of the linear actuators can be obtained as follow:

$$a = \frac{4Y - Y_0}{4} - \frac{m}{2} \tan \frac{\pi (\text{Pitch} - \text{Pitch}_0)}{180 \times 3600}$$
(10)

$$b = \frac{4Y - Y_0}{4} + \frac{m}{2} \tan \frac{\pi (\text{Pitch} - \text{Pitch}_0)}{180 \times 3600} + \frac{n}{2} \tan \frac{\pi (\text{Roll} - \text{Roll}_0)}{180 \times 3600}$$
(11)

$$c = \frac{4Y - Y_0}{4} + \frac{m}{2} \tan \frac{\pi (\text{Pitch} - \text{Pitch}_0)}{180 \times 3600} - \frac{n}{2} \tan \frac{\pi (\text{Roll} - \text{Roll}_0)}{180 \times 3600}$$
(12)



Fig. 9. Simulated results of the deformation of the push rod of vertical linear actuator. FEA: ANSYS 12.0, 3-D type, 90,204 elements, all the parts are assembled, and the contacts are defined for them, material is steel, load is 177.6 N.

$$e = \frac{2z - z_0}{2} + \frac{m}{2} \tan \frac{\pi (\text{Yaw} - \text{Yaw}_0)}{180 \times 3600}$$
(13)

$$f = \frac{2z - z_0}{2} - \frac{m}{2} \tan \frac{\pi (\text{Yaw} - \text{Yaw}_0)}{180 \times 3600}$$
(14)

When the Roll needs to be fine-adjusted to Roll+ Δ Roll, it is only to adjust *b* to $b = n/2 \tan(\text{Roll} + \Delta \text{Roll})$, and adjust *c* to $c = -n/2 \tan(\text{Roll} + \Delta \text{Roll})$. When the Pitch needs to be fine-adjusted to Pitch+ Δ Pitch, it is only to adjust *b* and *c* to $b = c = m/2 \tan(\text{Pitch} + \Delta \text{Pitch})$, and adjust *a* to $a = -m/2 \tan(\text{Pitch} + \Delta \text{Pitch})$. When the *Y* needs to be adjusted to *Y*+ Δ *Y*, it is necessary to adjust *a*, *b* and *c* to *Y*+ Δ *Y*. When the Yaw needs to be fine-adjusted to Yaw+ Δ Yaw, it is only to adjust *e* to $e = m/2 \tan(\text{Yaw} + \Delta \text{Yaw})$, and adjust *f* to $f = -m/2 \tan(\text{Yaw} + \Delta \text{Yaw})$. When the *Z* needs to be adjusted to *Z*+ Δ *Z*, it is necessary to adjust *e* and *f* to *Z*+ Δ *Z*.

Fig. 5 is the displacement functions of the vertical linear actuators, and the values of Roll₀, Pitch₀, Y_0 , Z_0 and Yaw₀ are zero. Fig. 5(a) is the function graph of displacement *a*. It is a binary function, and the independent variables are Y and Pitch. The graph is a three dimensional surface composed of many tangent curves which increase with the increase of the value of Y. Actually, the adjustable range of Y is -15 mm to 10 mm, and the adjustable range of Pitch is -0.5° to 2.0° , so the adjustable range of *a* can be further narrowed down, as shown in Fig. 5(b). In the adjustable range of Fig. 5(b), the



Fig. 10. Photo of the ARPES KB mirror system. It shows the assembling state in a cleaning room, the two reflectors have been installed in the frames, and the commissioning of *Y*, *Z*, Roll, Yaw and Pitch motions have been realized.

function graph is similar to an inclined plane, that is, there is almost a linear relationship between a and Y, so does Pitch. In Fig. 5(b), with the increase of Y, the value of a increases, and with the increase of Pitch, the value of a decreases. The adjustable range of a is about -19 mm to 11 mm.



Fig. 11. Photos of the testing process. (a) Shows that a vertical linear actuator is being tested by a laser interferometer, (b) shows that the Yaw motion is being tested by an autocollimation.



Fig. 12. Testing results of the vertical linear actuator. All the tests are finished on an air-floating platform (the vertical linear actuator and the laser interferometer are both on it) in order to reduce the vibration (Lee and Okwudire, 2016).

Fig. 5(c) and (d) is the function graph of displacement b. The Fig. 5(d) is the graph in the definitional domain (the adjustable range of Pitch is -0.5° to 2.0° , and the adjustable range of Roll is -1° to 1°). Because *b* is a function with three variables, it is necessary to get some hierarchical data to obtain the function graph, that is, a three dimensional graph corresponds to a value of Y, and its independent variables are Pitch and Roll. Fig. 5(c) and (d) is the three dimensional graph when Y=0, this graph is formed by many tangent curves which change in a tangent rule along Roll direction. In Fig. 5(c), the value of Roll is in a small range, so it does not present the tangent variation along the Roll direction. In definitional domain, the graph of displacement *b* is also similar to an inclined plane, because the tangent function is almost in a linear relationship when the independent variables are near the 0°. In Fig. 5(d), the value of *b* increases with the increase of Pitch, and increases with the increase of Roll. The adjustable range of b is about -1 mm to 6 mm when Y = 0. In order to obtain the actual adjustable range of b, the change of Y must be considered. b and Y are in a linear relationship, the adjustable range of Y is -15 mm to 10 mm, so the actual adjustable range of b is -16 mm to 16 mm.

Fig. 5(e) and (f) is the function graph of displacement c, the graph is very similar to the graph of b, the difference is that the value of c increases with the increase of Pitch, but decreases with the increase of Roll. When considering the change of Y, the actual adjustable range of c is about -16 mm to 16 mm.

Through above analysis, the analyzed results can be adopted to determine the key design parameters of the vertical linear actuators so as to guide the structure design. The displacement functions of the horizontal linear actuators are similar to the displacement functions of the vertical linear actuators, so they are not described in detail.

These functions not only can provide reliable information and guidance to the structure design, but also can provide reference value to test the performance of the alignment mechanism. In actual work, we need to test the displacement resolution and repeatability, and angle resolution and repeatability of the alignment mechanism. The testing results can be compared with the theoretical value in Fig. 5 so as to make an accurate evaluation on the performance of the alignment mechanism. The displacement functions can provide many adjusting information, such as adjusting parameters, adjusting direction, and adjusting step length to the expectant alignment of the mirror, thereby the adjusting time can be reduced greatly, and the veracity and efficiency of the alignment can be improved greatly, too.

Fig. 6 is the structure of the ARPES KB mirrors system, its core components are the support structure and the alignment mechanism. For the alignment mechanism, two horizontal linear actuators are inside the ultra high vacuum, and three vertical linear actuators are outside the ultra high vacuum, so the two horizontal linear actuators must have vacuum compatibility, and the three vertical linear actuators can feed in the vacuum. In order to guarantee the flux of the X-ray, the ARPES KB mirror system is operated in the 10^{-10} Torr vacuum. To guarantee the surface accuracy of the KB mirrors, they are equipped with a cooling device to make the thermal equilibrium be realized in a short time.



Fig. 13. Testing results of the Pitch motion. The measuring process is kept in an environment of vibration as small as possible.

3.2. Finite element analysis of the vertical linear actuator

The alignment mechanism not only needs accurate adjustment ability, but also needs a certain carrying capacity. The load carried by the horizontal linear actuator is very small owing to the adoption of a precision cross roller guide, thereby its carrying capacity is not considered. In fact, the mirror, mirror frame, horizontal linear actuators and other components are on the top of the three vertical linear actuator, therefore the carrying capacity of the vertical linear actuator needs to be considered. The reason is that its carrying capacity affects the adjusting accuracy of the mirror directly.

Fig. 7 is the force state diagram of the vertical linear actuator. *G* is the total weight of all the parts above the three vertical linear actuators. F_1 , F_2 and F_3 are the reaction forces of the three vertical linear actuators. The vertical linear actuator is in a quasi-static state because of its slow movement, so the *G* is balance with the F_1 , F_2 and F_3 . The limit position (2°) of Pitch is taken as the research object to analyze the force state of the vertical linear actuator, as shown in Fig. 8. The expressions can be obtained as follow:

$$\begin{cases} F_1 \cos \theta + (F_2 + F_3) \cos \theta = G \\ F_1 \sin \theta = (F_2 + F_3) \sin \theta \end{cases}$$
(15)

Through Eq. (15), we can calculate that $F_1 = F_2 + F_3 = G/2\cos\theta$. The total weight of mirror, mirrors frame and other parts is about 355 N, so $F_1 = F_2 + F_3 = 355 \text{ N}/2\cos2^\circ = 177.6 \text{ N}$.

For the linear actuator, the most concerned parameters are resolution and repeatability, because the resolution is related to the position accuracy of the mirror, and the repeatability is related to the ability how the mirror return to the previous state. The factors influencing the precision of linear actuator include thread pitch precision of ball screw, hysteresis of system and axial rigidity of system.

Travel of the vertical actuator is designed as -15 mm to 10 mm. But the actual travel is smaller, because the original position of alignment mechanism is designed to close to the theoretical position of mirror, therefore a ball screw with C3 level is adopted, whose deviation between actual moving distance and theoretical moving distance can reach to about 0.8 μ m during the 10 mm traveling. If the actual travel is smaller than 10 mm, the deviation will be less than 0.8 μ m. The smaller the travel is, the smaller the deviation is.

The hysteresis includes axial clearance of ball screw, lost step of motor, gap of three-point stage, and loosening of some parts. In order to reduce the hysteresis, a ball screw with zero axial clearance realized by an axial press and a high accuracy linear encoder



Fig. 14. The resolving power of the beamline. Slit size and slope error are considered in the calculation, and in order to achieve a higher resolving power at 1000 eV, a very high energy grating is used.

to realize a closed-loop control of motor are adopted, and all the parts are fastened. The ball screw with zero axial clearance is necessary for horizontal linear actuator, but not necessary for vertical linear actuator, because it always bears the axial load (gravity of the parts) during its adjusting process, the gravity makes the nut contact the ball screw tightly, hence, the hysteresis can be ignored. Similarly, for the three-point stage, the gravity of these parts make the conic surface, V-section trench, and hardened plane always contact the balls whatever the vertical linear actuators move upward or downward, so there is no gap between the balls and the three kinds of surfaces. Therefore, the structure of three-point stage has no or little contribution to the hysteresis of the KB mirror alignment mechanism.

For the horizontal linear actuator, the axial load is the friction force between all the parts over the sliding guide and sliding guide, it is small, and has less influence on the axial rigidity of the horizontal linear actuator. For the vertical linear actuator, it bears the axial load from gravity of all the parts upon it, the axial load will make the push rod of vertical linear actuator generate elastic deformation which will influence the precision of vertical linear actuator. Therefore, a detail analysis about the deformation of push rod is carried out in the paper. Based on the above description, the hysteresis will be ignored during the analysis.

The vertical linear actuator at A point (shown in Fig. 4) is taken as the research object, when its Pitch angle is at 0° and 2° respectively, the influence on the performance of alignment mechanism induced by the deformation of push rod is analyzed by FEA method.



Fig. 15. Photon flux at ARPES sample at a energy resolution 11 meV. The reflectivities of all mirrors are calculated by the data complied by Palik for photon energy lower than 30 eV and the optical constants in the Henke table at higher photon energy (Henke et al., 1993; Palik, 1997). The efficiency of grating is calculated by Neviere's code (Neviere et al., 1974).

The simulated results are shown in Fig. 9. The deformation of push rod includes axial deformation and radial deformation. When the Pitch angle is at 0° (Rollangle is also 0°), the alignment mechanism is in a horizontal position, and the load on the vertical linear actuator is in the same direction of the gravity, so the push rod mainly generates axial deformation, and the radial deformation is very small, as shown in Fig. 9(a) and (c). The biggest axial deformation is about $1.4 \,\mu\text{m}$, and the biggest radial deformation is about 0.14 µm. When the Pitch angle is at 2°, the angle between the direction of load borne by the vertical linear actuator and the direction of the gravity is 2° , in this condition, the push rod not only generates axial deformation, but also generates radial deformation, as shown in Fig. 9(b) and (d). The biggest axial deformation is about 1.7 µm, and the biggest radial deformation is about 0.15 mm. When the Pitch angle is 2°, the radial load on the top of the push rod is about 6.2 N, and the push rod is in a cantilever state, so it generates a large deflection. From Fig. 9, it can be seen that both axial deformation and radial deformation are in a linear relationship with the change of the length of the push rod. Within the category of elastic deformation, the axial deformation of push rod is in a linear relationship, the radial deformation along the length of push rod is in a cubic function relationship, but because the radial deformation is relatively small, the simulated results approximate the linear relationship.

In order to guarantee the linear resolution, linear repeatability, angle resolution and angle repeatability of the alignment mechanism, some high accuracy encoders from Renishaw Company are adopted to make a closed-loop control. The type of encoder is RGH22S15D61A. Its linear resolution is about 0.5 µm, so the Pitch angle resolution of the alignment mechanism can be calculated as $\alpha = \arctan h/m = \arctan (0.5 \,\mu\text{m}/240 \,\text{mm} = 0.43'')$. The grating scale of the encoder is RGS20-S, its repeatability is about 0.75 µm, hence, the corresponding Pitch angle repeatability is calculated as 0.65". In practice, the vertical linear actuator bears a certain load during the adjusting process, which will lead to the deformation of the push rod, and affect the performance of the vertical linear actuator. In 0° position, the biggest axial deformation is about 1.4 μ m, and in 2° position, the biggest axial deformation is about 1.7 μ m. From 0° to 2°, the variation of the effective length of the push rod in vertical direction is about 0.3 μ m, and the variation of the corresponding angle is about 0.26". Theoretically, the angle resolution is 0.43", so the vertical linear actuator can run 16,744 $(2^{\circ}/0.43'' = 16,744)$ steps from 0° to 2° . The deformation of the push rod is elastic deformation and relatively small, so the change of its



Fig. 16. Spot size of ray tracing result on the ARPES sample. Conditions: the very high energy grating is used; $10 \,\mu$ m exit slit; at $1000 \,\text{eV}$; the slope errors in Table 1 are considered.

effective length in vertical direction is close to a linear relationship. Consequently, the variation of the effective length of the push rod in vertical direction is about 0.0003 mm/16,744 = $1.8 \times 10^{-5} \mu$ m in each step, and the variation of the angle is about $1.6 \times 10^{-5\prime\prime}$ in each step. From above analysis, the linear resolution of vertical linear actuator turns to 0.5 μm +1.8 \times 10 $^{-5}$ $\mu m,$ and the angle resolution turns to $0.43'' + 1.6 \times 10^{-5''}$. It is easy to discover that the axial deformation has a very little influence on the resolution. Because the push rod generates elastic deformation, when the vertical linear actuator adjusts from 0° to 2° , the effective length of push rod in vertical direction decreases 0.3 µm, and when it adjusts from 2° to 0° , the push rod returns to the initial length. Therefore, for the same position, the repeatability of the vertical linear actuator is unchangeable, or the variation is very small in theory. Fig. 9(c) and (d) shows the radial deformations of the push rod in positions 0° and 2° . In position 2° , the biggest radial deflection is 0.15 mm, so the distance between the two support points turns to 240.3 mm, and the angle resolution can be recalculated as about 0.43". In 0° position, the biggest deflection is $0.1 \,\mu\text{m}$, whose influence on the resolution can be neglected. Also, from 0° to 2°, the radial deformation increases, and from 2° to 0° , the radial deformation decreases, and then returns to the initial state. Therefore, for the same angle, the repeatability is unchangeable, or the variation is very small. From above analysis, we can find that under the reasonable load, the influence of the deformation on the resolution and repeatability is within the scope of permissible error.

4. Testing of the mechanical performance for KB mirror system

Fig. 10 shows the photo of the ARPES KB mirror system. In order to meet the requirements of the dreamline, it is necessary to test the main technical parameters, including linear resolution and repeatability, and angle resolution and repeatability. In practice, the linear resolutions and repeatabilities of all the linear actuators, and the angle resolutions and repeatabilities of the alignment mechanism are tested. In the paper, the performance of vertical linear actuator and the testing results of Pitch angle are presented. A laser interferometer Agilent 5529A with ± 1 ppm/0–40 °C precision is adopted to test the linear resolution and repeatability, shown as Fig. 11(a); an autocollimation ELCOMAT 3000 with 0.1" precision is adopted to test the angle resolution and repeatability, shown as Fig. 11(b).

Fig. 12 is the testing results of the linear actuator. In order to obtain its resolution, five positions within the travel range are tested. The step length is set as $0.5 \,\mu$ m, and the laser interferometer records the reading in each step (10 steps are run). In the positions of 0 mm, 5 mm, 15 mm and 20 mm, the biggest average difference

in each step is about 0.56 μ m. Therefore, the resolution of the linear actuator is considered as 0.56 μ m when the step length is 0.5 μ m. In addition to the resolution, repeatability is another important technical parameter for the linear actuator, it ensures the recover ability of the position. Eight positions within the travel range are tested along horizontal unidirection. The distance between the neighboring positions are 5 mm. The standard deviations of the eight sets of data are 0.49 μ m, 1.17 μ m, 1.6 μ m, 0.91 μ m, 1.36 μ m, 0.39 μ m, 1.57 μ m and 0.43 μ m respectively. The biggest value 1.6 μ m is considered as the repeatability of the linear actuator.

Fig. 13(a) is the testing results of Pitch angle. Three positions are tested to gain the angle resolution. The step length is set as 0.0002° , and the autocollimation records the reading in each step. In position -1° , the average value is about 0.6''; in position 0° , the the average value is about 0.57''; in position 1° , the average value is about 0.55''. Therefore, the Pitch angle resolution is considered as 0.6'' when the step length is 0.0002° . The autocollimation is adopted to test the unidirectional repeatabilities in the positions of -1° , -0.5° , 0° , 0.5° and 1° . Fig. 13(b) shows the standard deviations of the five positions, they are 1.06'', 0.98'', 0.78'', 0.85'' and 1.08'' respectively. The biggest value 1.08'' is considered as the repeatability of the Pitch angle.

Through above testing results, it can be seen that the resolutions and repeatabilities of the linear actuator and Pitch angle meet the requirements. The testing process of the other parameters is similar to the above description, and the testing results are better than the technical requirements.

5. Evaluation of the performance of ARPES beamline

KB mirror system is very important for the ARPES beamline, but for the end-users, they are concerned only with its total performance. Therefore, the energy resolution, the photon flux and the monochromatic light spot size of the beamline are described in this section.

Through calculation, the energy resolutions of the beamline by four gratings are shown in Fig. 14. It can be seen that the resolving power at 1000 eV is about 89,000, and the energy resolution is about 11.2 meV.

Fig. 15 is the photon flux at ARPES sample at an energy resolution 11 meV. The photon flux is higher than 10¹¹ phs/s/0.01%BW from 20 eV to 1000 eV for both linear and circular polarizations. There is a increase for the middle energy grating when switching from low-energy insertion device to high-energy insertion device.

Besides energy resolution and photon flux, the quality of light spot is another key index, and the purpose of KB mirrors is to get a high quality focusing spot. Fig. 16 shows the ray tracing result by the KB mirrors on the sample for 1000 eV using a very high energy grating with 10 μ m exit slit. During the ray tracing, the slope errors of the optical elements are included. From Fig. 16, it can be seen that the spot size is about 15 μ m × 4.7 μ m (FWHM), and it meets the requirement.

6. Conclusions

A new ARPES KB mirror system of the dreamline for SSRF is developed. The design scheme of the key component—alignment mechanism is presented. The principle and working process of the alignment mechanism are analyzed, and practical significance of the displacement function to guide the alignment of the KB mirrors is discussed. The variation of resolution and repeatability of the mirror induced by axial deformation and radial deformation of the vertical linear driving mechanism is analyzed, it is within the scope of permissible error. The mechanical performance of KB mirror system is tested, the results show that linear resolution and repeatability, and angle resolution and repeatability are 0.56 μ m, 1.6 μ m, 0.6" and 1.08" respectively, which guarantee the performance of the beamline. After simulation and ray tracing, it is found that the energy resolution is better than 11.2 meV at 1000 eV, the photon flux is higher than 10¹¹ phs/s/0.01%BW and the spot size on sample is about 15 μ m × 4.7 μ m (FWHM) for the beamline, whose performance is higher than the expected evaluation.

Acknowledgments

This work was funded by National Nature Science Foundation of China (No. 61404139), Independent fund of State key laboratory of applied optics (Y5743FQ158), and Key Science and Technology Achievements Transformation Projects of Jilin Province (20150307039GX).

The authors thank the staff of dreamline at Shanghai Synchrotron Radiation Facility.

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