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HIGH-PRECISION POSITIONING DESIGN FOR SYNCHROTRON RADIATION INSTRUMENTATION

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HIGH-PRECISION POSITIONING DESIGNS FOR SYNCHROTRON RADIATION INSTRUMENTATION

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Abstract

High-precision positioning devices are used extensively in synchrotron radiation instrumentation. This paper will give an overview of micro- and nano-positioning designs for synchrotron radiation instrumentation applications. The topics include:

- *Linear micro-positioning devices for supporting structures*
- *Angular positioning devices for x-ray instruments*
- *In-vacuum micro-positioning devices design*
- *Nano-positioning devices design*

Several practical design examples will be discussed in this paper.

1. Introduction

At the third-generation hard x-ray synchrotron radiation sources, such as the Advanced Photon Source (APS) at Argonne National Laboratory, precision positioning techniques present a significant opportunity to support the state-of-the-art synchrotron radiation research. Today you may find more than thirty motorized positioning devices in a single experimental station or 100 – 150 remote-control positioning channels in a single beamline control system at the APS. These positioning devices provided remote accessibility to the beamline components and instruments inside the radiation shielding enclosure. Furthermore, their positioning performances and capabilities, such as resolution, repeatability, speed, and multiple axes synchronization are exceeding the limit that a manual control system can reach.

Compared with customized design, commercialized positioning devices always have better performance/cost ratio because they are mass produced. For the APS beamline instrumentation development, when there are no commercial products available, a customized device will be developed with a modular design consideration to improve cost effectiveness. In the past ten years, a series of modularly designed precision positioning devices have been developed at the APS. This paper presents an overview of these customized precision positioning device designs. In the section on in-vacuum micro-positioning devices, custom stages developed by the European Synchrotron Radiation Facility (ESRF) are also introduced along with APS custom products.

2. Micro-positioning devices for supporting structures

Located inside of the radiation shielding enclosure, many beamline optical components and experimental instruments need to be positioned and supported with high precision. A typical beamline component may weigh 50 – 500 kg. A 10-micron or better positioning resolution with 25 – 200 mm travel range usually is needed for alignment with x-ray beam from an undulator or bending magnet source. Dependent on the type of the application, multi-dimensional positioning with angular adjustment may be required.

2.1. Modular linear stage design

A numbers of linear stages have been developed at the APS as the basic functional modules for the various supporting applications. Commercial cross-roller bearings and stepping-motor driving systems are used in most of the stages. Spring-loaded linear potentiometers with 10-µm repeatability have been applied as absolute position sensors for all of the modules. For most of the heavy-load stages, a 200-µrad/25-mm straightness of trajectory has been achieved. For medium-load stages such as the T2-24 vertical stage, a 10-µrad/5-mm straightness of trajectory was demonstrated in the test [1,2,3]. Table 1 summarizes the design specifications of several of the most commonly used linear stages.

Table 1: Design specification of the APS linear stage modules

Name*	***Description***	***Dimension (mm)WxLxH***	***Max. load (kg)***	***Range (mm)***	***Resolution (mm)***	***Repeatability (mm)***
T2-24	*Vertical*	*146x146x127*	*23*	*12.7*	*1*	*5*
T2-26	*Vertical*	*146x146x203*	*90*	*50*	*0.5*	*5*
T2-81	*Vertical*	*200x241x170*	*90*	*12.7*	*0.1*	*2*
T4-21	*Vertical*	*205x205x225*	*454*	*25*	*2*	*10*
T4-22	*Vertical*	*205x205x365*	*454*	*100*	*2*	*10*
T4-25	*Vertical*	*205x205x275*	*454*	*50*	*2*	*10*
T2-22	*Single Horizontal*	*200x221x28*	*90*	*12.7*	*2.5*	*10*
T2-25	*Single Horizontal*	*152x235x51*	*136*	*50*	*1.6*	*5*
T4-61	*Single Horizontal*	*220x518x87*	*454*	*150*	*2*	*10*
T4-62	*x-y Horizontal (y free)*	*220x518x87*	*454*	*x150 y54*	*x2*	*x10*
T4-63	*x-y Horizontal (xy free)*	*220x340x87*	*454*	*x175 y54*		
T4-64	*x-y Horizontal*	*220x518x87*	*454*	*x150 y54*	*x2 y2*	*x10 y10*
T4-65	*Single Horizontal*	*220x398x87*	*454*	*25*	*2*	*10*
T4-66	*x-y Horizontal (y free)*	*220x398x87*	*454*	*x25 y54*	*x2*	*y10*
T4-67	*x-y Horizontal (xy free)*	*220x205x87*	*454*	*x25 y54*		

* drawing name in the APS design exchange system, visit web site http://dxchange.aps.anl.gov for further information.

2.2. Stacking single support system

The stacking single support system has been used at the APS for positioning medium-sized beamline components such as x-ray beam position monitors, slits, compound refraction lenses, etc. Figure 1 shows undulator x-ray white beam slits with compound refraction collimating lenses in the first optical enclosure at the APS sector 3 [4,5]. Its support system includes three stacking single supports. As a slit-positioning device, three stages (one T2-81 vertical stage, one T2-22 horizontal stage, and a rotary alignment stage) are stacked together to perform the x-z-yaw positioning function. This configuration has also been used for the APS undulator front end x-ray beam position monitor support shown in Fig. 2. Since the x-ray compound refraction collimating lenses need x-z-yaw-pitch positioning capability, a commercial angular stage was added in this configuration.

Fig. 1. Photograph of the undulator x-ray white beam slits with compound refraction collimating lenses in the first optical enclosure at the APS sector 3.

2.3. Kinematic mounting support system

A series of kinematic mounting tables has been developed at the APS in support of optics and instrumentation for synchrotron radiation research. The basic precision motion design uses the 3-point "cone-flat-V" kinematic mount concept obtained through the use of modular linear rolling stages and ball-bearing spherical joints as shown in Fig. 2 [1]. The "cone-flat-V" kinematic mount concept has the advantages of 3-point stability, reduced space usage, minimal motor drivers, free and unconstrained thermal expansion, and good positioning repeatability.

For example, as show in Fig. 3, in the T6-36 x-ray mirror support design, cooperated with a vertical stage T4-21 and a spherical joint, the x-y horizontal stage T4-61 (single-axis motor-driven stage) simulates the "cone" function in the 3-point "cone-flat-V" kinematic mount concept. With same type of vertical stage and spherical joint, the x-y free-sliding stage T4-63 simulates the function "flat" and the x-y horizontal stage T4-62 (x axis is motor driven and y is a free slide) simulates the function "V". The T6-36 mirror support provides five-degrees of the freedom precision positioning capability with micron-level motion resolution.

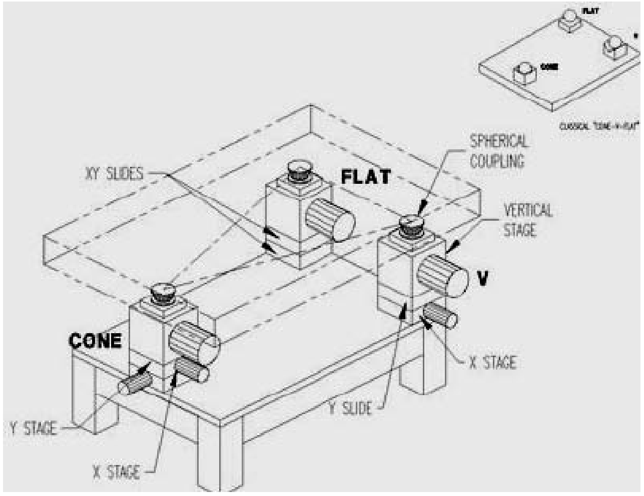

Fig. 2. Design using the 3-point "cone-flat-V" kinematic mount concept obtained through the use of modular linear rolling stages and ball-bearing spherical joints..

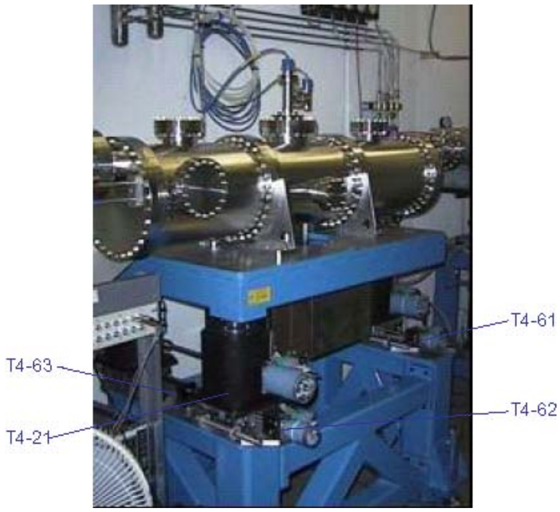

Fig. 3. Photograph of the APS T6-36 x-ray mirror support at the APS sector 1

2.4. Hybrid support system

As an optical table for an experimental station, the T6-47 table incorporates the large vertical axis manual motion necessitated by flexible x-ray optics arrangements and a variety of experimental instrument setups. As shown in Fig. 4, the base assembly provides large vertical motion using three worm-gear actuators to lift a rigid inner frame [1]. Once the table is positioned at the desired height, stability is maintained by locking the inner frame to the outer frame using thrust screws. The thrust screws counteract any lateral movements that may occur at any position. In conjunction with the manual motion, the T6-47 table also provides high precision motion using modular high-load-capacity positioning stages arranged in the 3-point kinematic concept similar to the T6-36 mirror support. The T6-47 has six degrees of freedom positioning capability because its "cone" function performed with a dual motor-driven axes x-y stage T4-64. The T6-47 provides free choice of rotation point at arbitrary location on the table through use of multiple simultaneous motion programmed with a rotation matrix.

Fig. 4. Photograph of the APS T6-47 optical table for experimental station.

The T6-42 table supports a 6-circle goniometer instrument as shown in Fig. 5. The goniometer's tall profile and its large travel range requirements led to a lower profile design comprised of a rigid 3-point frame, secured to the floor, which guides and locks a primary frame holding the precision stages and slides [1]. As with the T6-47 table, three worm-gear actuators lift and support the primary frame to any height, relative to the post frame, and are locked into position with a set of thrust screws to counteract lateral movements. The precision motions with six degrees of the freedom are performed using three modular vertical stages T4-22 and three horizontal x-y stages T4-62, T4-63, and T4-64 in the 3-point kinematic concept.

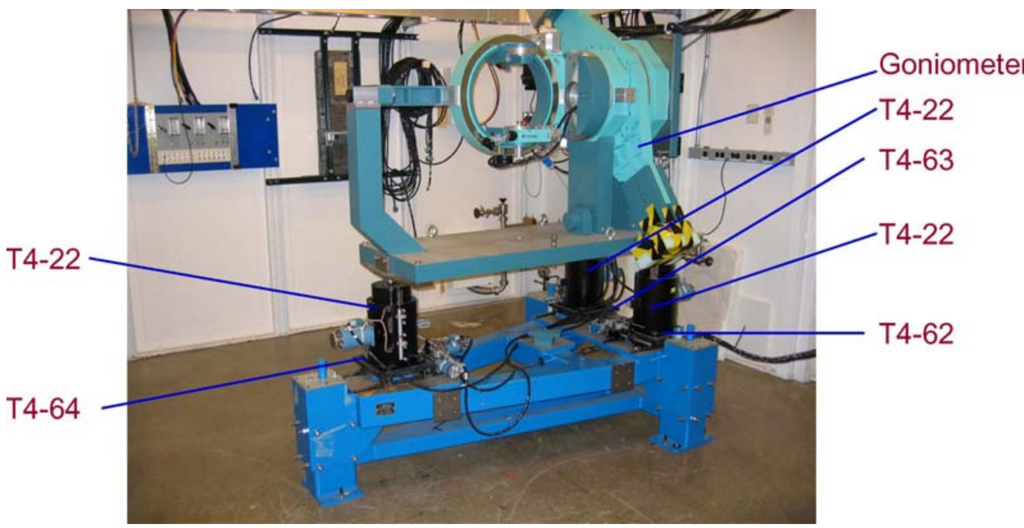

Fig. 5. Photograph of the APS T6-42 6-circle goniometer suppoting table.

In the applications of x-ray optics positioning, a specific motion direction may need to be more precise than any other degrees of freedom. In these cases, in conjunction with the standard 3-point kinematic system, an extra fine motion stage was added to the system to meet the x-ray optics positioning requirement. For instance, a special vertical stage was included in the T6-39 table for a large precision vertical motion required by the x-ray multilayer monochromator, as shown in Fig. 6. Another example of such a hybrid design is the mirror support table T6-51. A high-resolution angular stage was combined with the kinematic mounting support system to perform a fine adjustment for horizontal deflection x-ray mirror, as shown in Fig. 7. Table 2 summarizes the design specifications for several of the most commonly used APS kinematic mounting support systems.

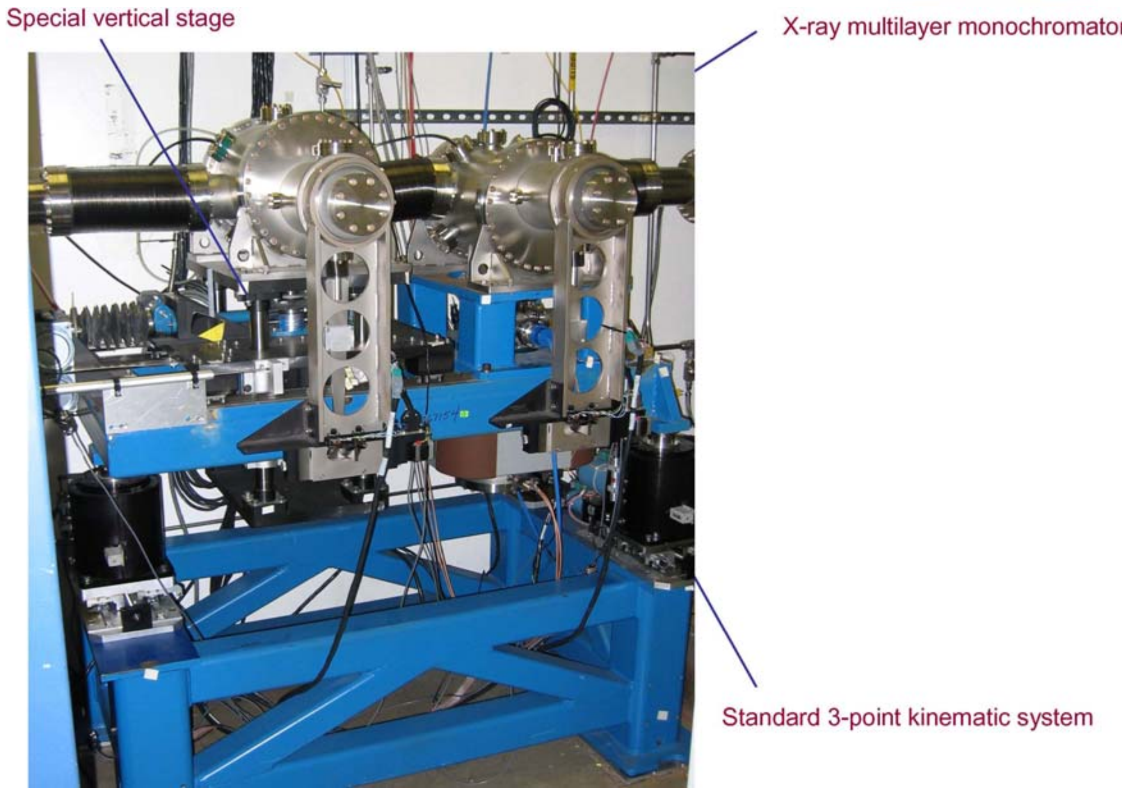

Fig. 6. Photograph of the APS T6-39 x-ray multilayer monochromator support at the APS sector 2.

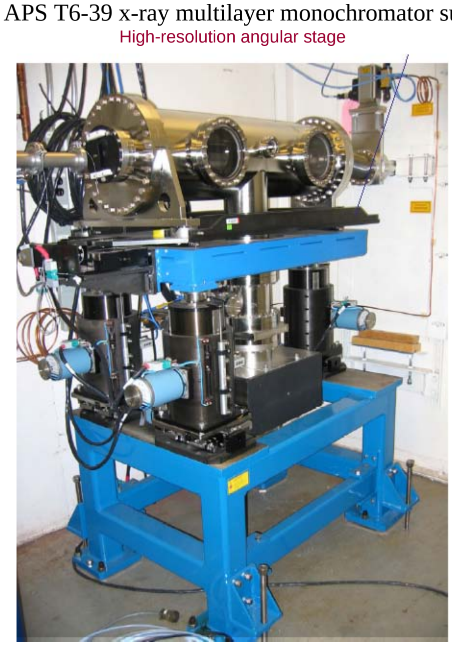

Fig. 7. Photograph of the APS T6-51 hybrid x-ray mirror support at the APS sector 32.

Table 2: Design specifications for the APS kinematic mounting support system

Name*	***Description***	***Dimension (mm)WxLxH***	***Max. load (kg)***	***Linear stage modules used***
T6-47	*Optical table for experimental station*	*914x1514x1124*	*454*	*Vertical T1-92 x3 Horizontal: T4-62, T4-63, T4-64*
T6-42	*Goniometer support for experimental station*	*1162x1730x807*	*1000*	*Vertical: T4-22 x3 Horizontal: T4-62, T4-63, T4-64*
T6-36	*X-ray mirror support*	*660x1118x1108*	*1000*	*Vertical: T4-21 x3 Horizontal: T4-61, T4-62, T4-63*
T6-51	*X-ray mirror support with fine yaw-stage*	*457x920x1223*	*1000*	*Vertical: T4-22 x3 Horizontal: T4-65, T4-66, T4-67*
T6-39	*X-ray Monochromator support*	*914x1511x994*	*1000*	*Vertical: T4-21 x3 Horizontal: T4-61, T4-62, T4-63*

* drawing name in the APS design exchange system, visit web site http://dxchange.aps.anl.gov for further information.

3. Angular positioning devices for x-ray instruments

Commercial angular positioning devices are used extensively in x-ray instrumentation applications. From monochromators, to spectrometers to diffractometers, industrial products provide many practical design choices. Precision worm-gear-based rotary tables equipped with high-resolution rotary grating encoders with 360 degrees positioning capability are popular for the precision goniometer design. A goniometer with 45-nrad angular resolution with 20-kg load capacity is commercially available [6]. To further improve the positioning performance, brushless servomotors may be integrated with the rotary stage to perform a direct drive. In this section, APS-developed customized angular positioning techniques are introduced.

3.1. Rotary table for horizontal reflection x-ray mirrors

For angular positioning with limited rotation range, various sine-bar mechanisms are used in many x-ray optical instruments. Figure 8 shows the design of a high-resolution angular adjustment platform for the horizontal deflecting x-ray mirror support table T6-51. A commercial linear stage (MTM 100 from Newport Co.) was used as a driver for the sine-bar mechanism. A pair of circular curved rolling guides supports the mirror chamber and defines the center of rotation for the sine-bar mechanism. With a 600-mm-long sine-bar and a 0.1-μm resolution linear stage, this platform provides a 170-nrad angular positioning resolution with 454-kg load capacity.

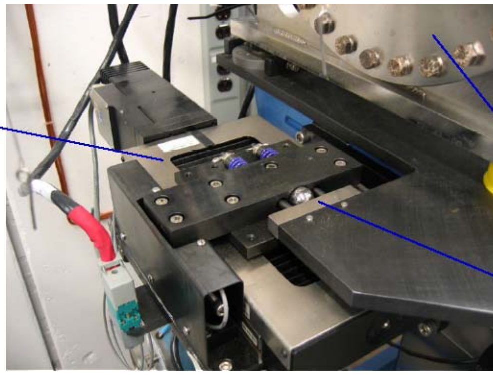

Fig. 8. Photograph of the high-resolution angular adjustment platform for the horizontal deflecting mirror.

3.2. Angular motion platform for x-ray spectrometer

A 6 meter-long-x-ray spectrometer has been developed for inelastic x-ray scattering applications at the APS sector 3 [7]. As shown in Fig. 9, a group of four crystal analyzers are located at one end of the rotating beam-path arm and supported by a pair of linear stages. The detector is mounted on the other end of the arm and supported by a pair of circular curved rolling guides mounted on a typical APS kinematic mounting support table. Driven by the 2-meter-long linear stage, the spectrometer can perform an 18-degree angular motion. To improve the lateral stiffness of the arm supporting structure, an extra section of circular curved rolling guide may be added to the system.

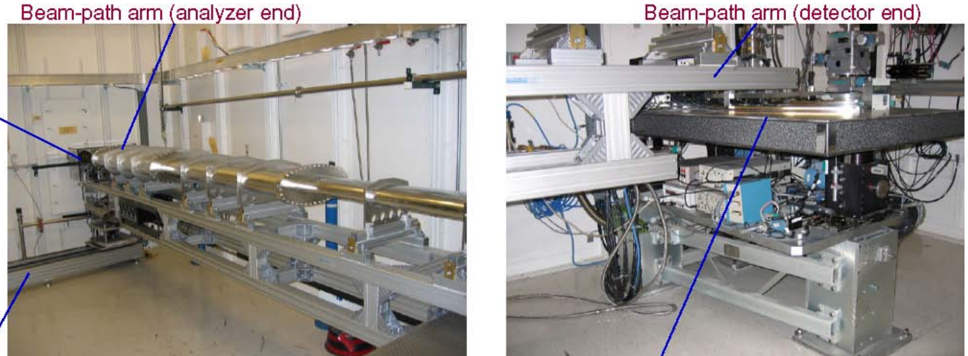

Fig. 9. Photograph of the angular motion platform for a 6 meter long x-ray spectrometer at the APS sector 3.

3.3. Weak-link mechanism for high-energy-resolution x-ray monochromator

A novel miniature overconstrained weak-link mechanism that allows positioning of two crystals with better than 30-nrad angular resolution has been developed at the APS [8,9]. The precision and stability of this structure allow the user to align or adjust an assembly of crystals to achieve the same performance as a single channel-cut crystal, so we call it an “artificial channel-cut crystal.” The availability of this novel mechanism makes life easier for novel x-ray crystal optics developers, because of the possibility of free-to-use asymmetric-cut crystals in monochromator design to improve angular acceptance and energy resolution [10]. It also provides the capability to perform a dynamic angular adjustment for temperature compensation between two crystals. In the past five years, more than 18 sets of overconstrained weak-link mechanisms have been constructed for high-energy-resolution monochromator applications at the APS. The applications were also expanded to the high-resolution crystal analyzer and the analyzer array for x-ray powder diffraction instrumentation. Figure 10 shows a rotational stage using an overconstrained weak-link mechanism for the National Institute of Standards and Technology’s (NIST) ultra-small-angle x-ray scattering instrument at the APS UNICAT sector 33 experimental station [11].

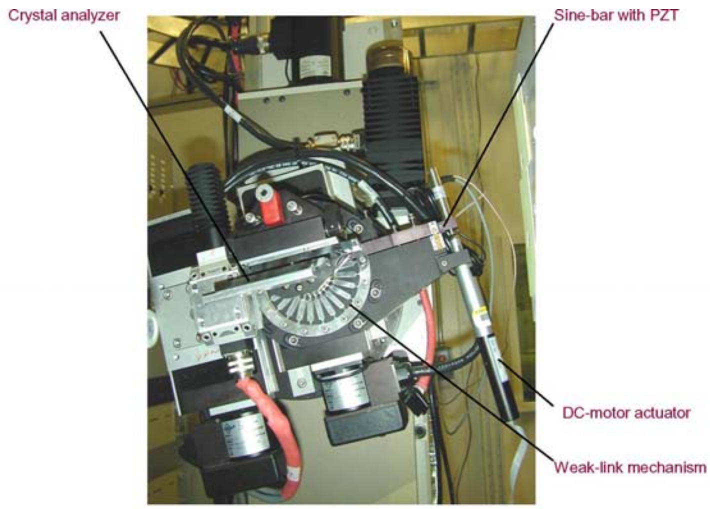

Fig. 10. Photograph of the rotational stage using an overconstrained weak-link mechanism for the NIST ultra-small-angle x-ray scattering instrument at the APS UNICAT sector 33.

Unlike traditional kinematic linear spring mechanisms, the overconstrained weak-link mechanism provides much higher structure stiffness and stability. Using a laminar structure configured and manufactured by chemical etching and lithography techniques, we are able to design and build a planar-shape, high-stiffness, high-precision weak-link mechanism as show in Fig. 11. The structure consists of three subassemblies: one base structure and two crystal holders. The base structure includes a compact sine-bar driving mechanism for the crystal pitch alignment, which is the key component of the structure as shown in Fig. 12.

maximum von Mises stress 175 MPa

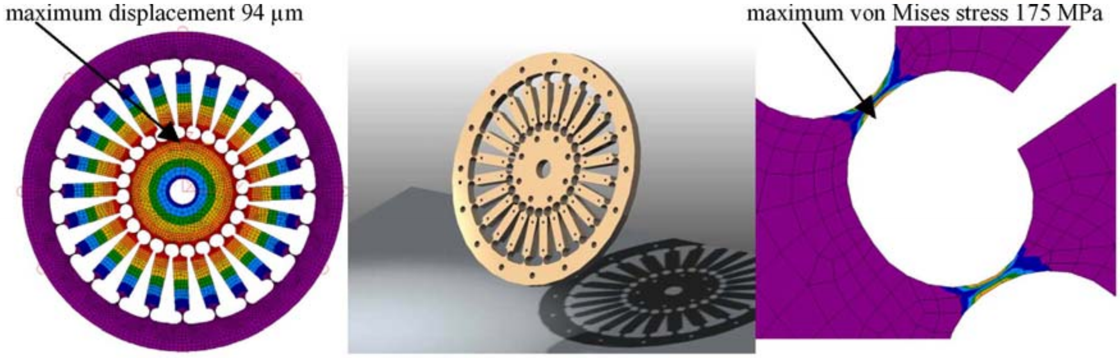

Fig. 11. A finite element simulation for the planar-shape weak-link displacement under a 0.89-Nm torsion load. The left side shows the distribution of displacement, and the right side shows the distribution of stress in an enlarged zone.

The precision of modern photochemical machining processes using lithography techniques makes it possible to construct a strain-free (or strain-limited) overconstrained mechanism on the thin metal sheets. By stacking these thin-metal weak-link sheets with alignment pins, we can construct a solid complex weak-link structure for a reasonable cost.

We have tested the sensitivity of the weak-link sine-bar structure with a laser Doppler angular encoder with nanoradian sensitivity. During the test, a series of 5-nm incremental steps is applied to the sine-bar by the PZT. The average angular step size measured by the laser Doppler angular encoder is 33 nrad with a 7-nrad rms deviation, which meets the design specification for the weak-link mechanism.

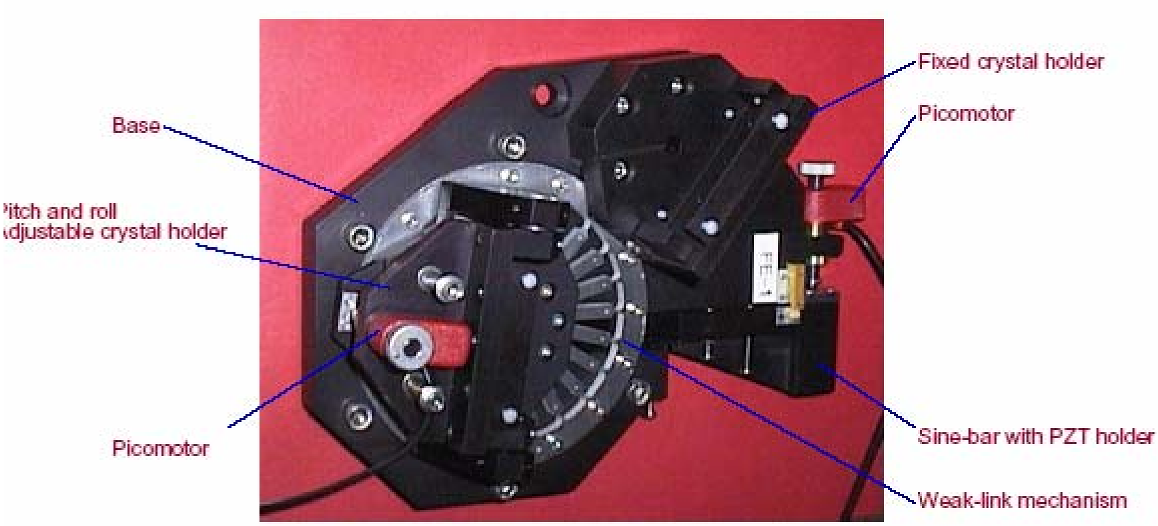

Fig. 12. Photogragh of the high-energy-resolution x-ray crystal monochromator with laminar overconstrained weak-link mechanism.

We have tested the second prototype artificial channel-cut crystal as an outer crystal for a 4-crystal in-line high-resolution monochromator with nested configuration at the APS 3-ID-B experiment station. The outer crystals of the monochromator are asymmetrically cut silicon (4 4 0), and the inner channel-cut crystal is silicon (15 11 3). This combination yields a bandpass of 1 meV at 21.6 keV. The monochromator is tunable between 21.5 - 21.7 keV. A sixty-minute intensity stability test result shows that the change in transmitted intensity is less than 25 nrad per hour with a 1-meV bandwidth monochromatic beam. The change in transmitted intensity reflects the combined change in beam position, thermal changes, and crystal-angle variations. At this point we have not isolated the contribution of the artificial channel-cut crystal assembly alone [8].

4. In-vacuum micro-positioning devices design

Many synchrotron radiation instruments require high-vacuum (HV) or ultra-high-vacuum (UHV) compatibility. Special design practices need to be established for the HV- or UHV-compatible device to minimize the gas load and maximize the pumping speed. The major design considerations for an HV-or-UHV-compatible device include:

- Selecting the HV- or UHV-compatible material with which to construct the device
- Minimizing the device surface area open to vacuum
- Eliminating any trapped volumes in the device and component design
- Selecting the proper surface quality and manufacturing process
- Compatibility with cleaning process and bake temperature
- Selecting the proper material for friction pair
- Selecting the proper cooling method
- Mechanical stabilizing under vacuum force

4.1. Precision vacuum feedthrough

There are two different ways to positioning an object in the vacuum: with a set of vacuum compatible positioning stages or with a conjunction of a set of regular stages and a precision vacuum feedthrough. Using a vacuum feedthrough is the best way to minimize the device surface area open to vacuum.

The second mirror chamber at the APS beamline 2-ID-A is a vacuum vessel for three mirrors that switch the beam into the 2-ID-B and 2-ID-C beamline branches horizontally. As shown in Fig. 13, the Y4-20-C mirror receives an incident beam that is reflected by the 2-ID first mirror and deflects it to the 2-ID-C branch by an angle of 2.5° from the incident beam. The cutoff energy of Y4-20-C is 3 keV. To switch the beam into the 2-ID-B branch, the Y4-20-C mirror can be moved out of the beam. The Y4-20-B1 mirror then receives the beam reflected by Y2-20 and deflects it by 2.5° to the Y4-20-B2 mirror, which deflects the beam by another 2.5°. The 2-ID-B branch accepts the beam reflected by Y4-20-B2. When all of the mirrors in the second mirror chamber (Y4-20) are moved out of the beam, the beam reflected by Y2-20 is delivered into the 2-ID-D/E branch [12].

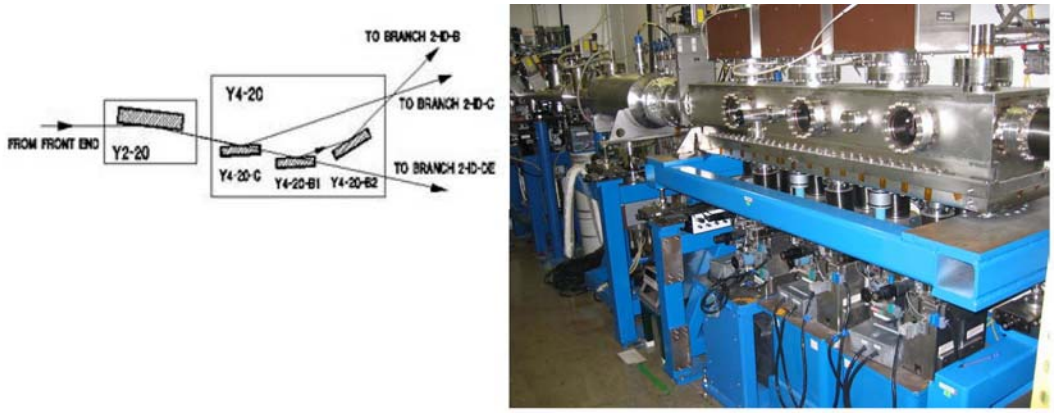

Fig. 13. Schematic diagram of the 2-ID beamline branches and photograph of the Y4-20 multi-mirror system at 2-ID-A station.

A modular, UHV-compatible mirror support and manipulator system has been designed and constructed for the three mirrors in 2-ID Y4-20-B1, Y4-20-B2, and Y4-20-C, as shown in Fig. 14 [12]. There are three mirror-mount platforms inside the vacuum chamber. Each platform is attached via three self-aligned ball bearings to three vertical posts, which also function as vacuum feed-through components with welded bellows. Each vertical post is mounted on the top of a pair of orthogonal stacked horizontal stages/slides, then assembled on the precision vertical stage. Similar to the T6-36 mirror support table, this mirror manipulator is a “cone-v-flat” equivalent rolling kinematic mounting structure. To improve the system stiffness, an extra stiffener platform is attached via three self-aligned ball bearings to the base of the three vertical posts. The water supply pipes for the mirror side-cooling structure are through the center hole of the manipulator post with a UHV mini-flange. No water-to-vacuum joints exist in this design. The specifications for this UHV mirror-mount actuator/stage system are shown in Table 3 [12]. The large vertical travel range of the manipulator allows users to move the mirror out of the beam or to choose a different coating strip on the mirror surface. The Y4-20 multi-mirror system at APS 2-ID-A has been operational since 1998.

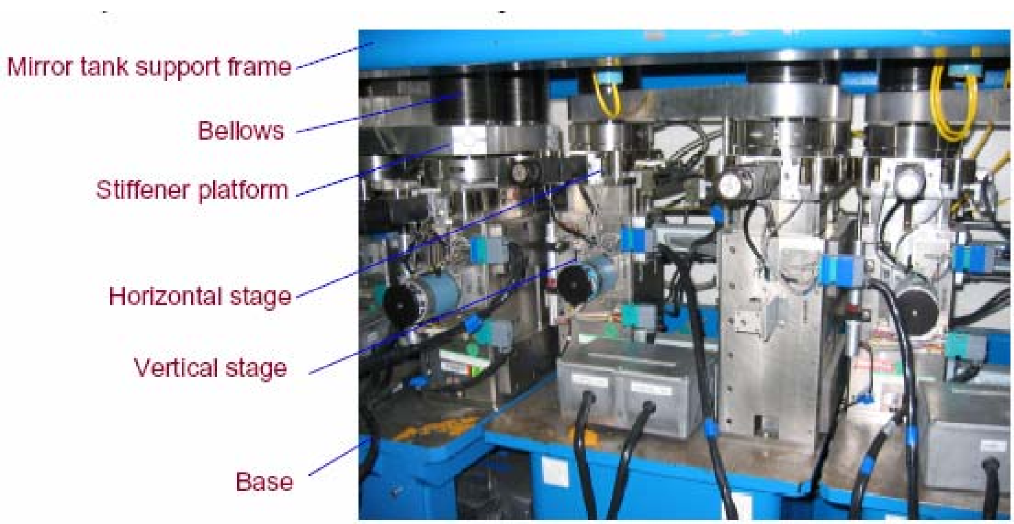

Fig. 14. Photograph of the “cone-v-flat” equivalent rolling kinematic mounting structure for Y4-20 mirror manipulator system.

Table 3: Design specification of the APS Y4-20 mirror supporting system

Load capacity	*227 kg*
Degrees of freedom	*5*
Vertical travel range	*60 mm*
Horizontal travel range	*12 mm*
Vertical motion resolution	*0.3 µm*
Vertical motion repeatability	*3 µm*
Horizontal motion resolution	*0.1 µm*
Horizontal motion repeatability	*1 µm*
Straightness of Trajectory	*10 µrad/5mm*
Pitch angle resolution	*0.33 µrad*
Roll angle resolution	*2.4 µrad*
Yaw angle resolution	*1.1 µrad*

4.2. In-vacuum precision stages

A set of HV-or UHV-compatible high-precision high-stiffness custom translation tables have been developed by Y. Dabin et al. at the ESRF for x-ray microscopy applications [13]. Figure 15 and 16 show the structure of the horizontal and vertical stages with overconstrained design [14]. The transverse stiffness comes from the ball/slide system [15]. It is pre-loaded in terms of diameter oversizing between 2 and 9 µm given by the ball selection (made of ceramic of steel). Special care has been taken for clamping of the guide bars that allow distance/parallelism tenability. Table 4 summarizes the tested performances of the ESRF stages. The ESRF ID21 microscope is composed of a set of eight such custom stages operated under 10^{-6} mbars [13].

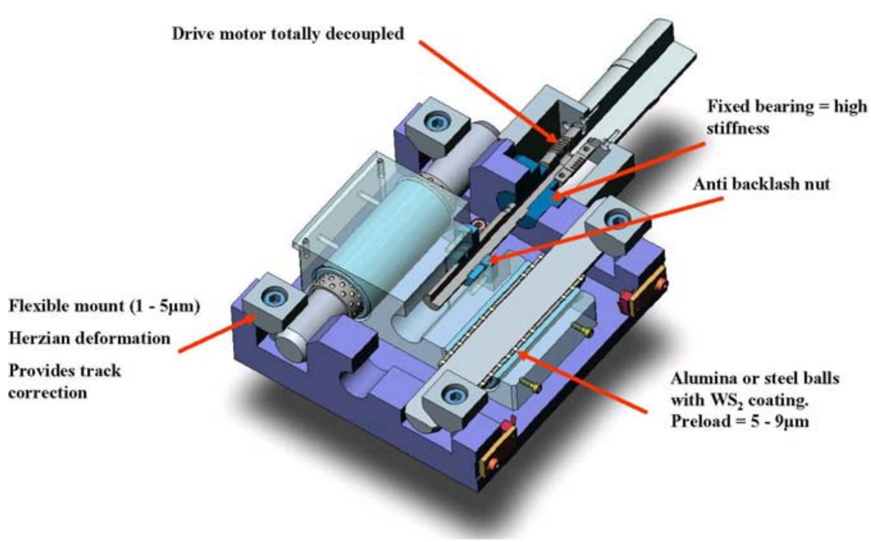

Fig. 15. Structure diagram of the ESRF horizontal stage with overconstrained design.

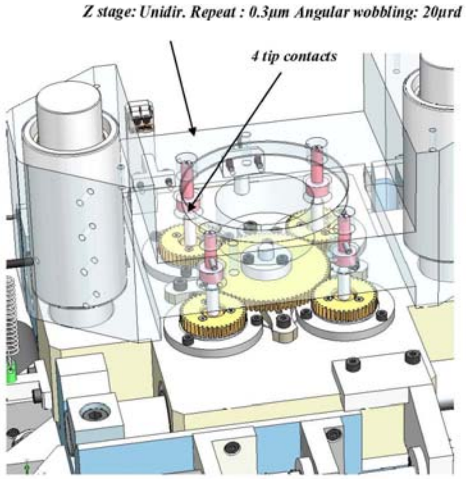

Fig. 16. Structure diagram of the ESRF vertical stage with overconstrained design.

Table 4: Tested performances of the ESRF ID21 in-vacuum stages [13]

Name	***Prototype***	***Stage 1***	***Stage 2***	***Stage 3***	***Stage 4***
Travel Rage (mm)	*85*	*90*	*90*	*9*	*7.5*
Resolution (µm)	*0.2*	*0.2*	*0.2*	*0.1*	*0.1*
Unidirectional Repeatability (µm)	*2*	*1*	*1*	*0.15*	*1*
Bidirectional Repeatability (µm)	*6*	*10*	*5*	*9*	*5*
Roll angular error (µrad)	*14*	*49*	*30*	*57*	*8*
Pitch angular error (µrad)	*22*	*25*	*17*	*4*	*11*
Yaw angular error (µrad)	*21*	*7*	*19*	*6*	*8*

When compared with vacuum feedthrough, the big advantage in using in-vacuum stages is that there is no vacuum force that directly acts on the motion object. Precision motion with high-resolution and repeatability will be achieved without the disturbance of the variable vacuum force. With improvements in the commercial availability of the HV-or UHV-compatible basic motion components such as motors, encoders, and limit switches, more complex systems will choose in-vacuum stage designs in the future.

5. Nano-positioning devices design

Instrument developers at the APS are facing many technical challenges. One of the challenges is to develop a state-of-the-art linear stage system for x-ray instruments with ultrahigh resolution, stability, and a large dynamic range, such as an ultraprecision scanning stage system for an x-ray nanoprobe with pixel repeatability in the nanometer scale [16]. There are two major ultraprecision motion-control techniques that have been developed for this challenging task.

- A novel laser Doppler encoder system with multiple-reflection optics.
- A specially designed high-stiffness weak-link mechanism with stacked thin metal sheets having sub-100-pm driving sensitivity with excellent stability [8,9].

In this section, we present recent progress towards development of an ultraprecision linear stage system for hard x-ray nanoprobes.

5.1. Laser Doppler encoder with multiple-reflection optics

Since 1998 a prototype laser Doppler linear encoder (LDLE) with multiple reflections has been under development at the APS [17,18,19]. With a customized commercial laser Doppler displacement meter (LDDM) [20], this novel linear encoder achieved sub-100-pm sensitivity in a 300-mm measuring range. The LDDM is based on the principles of radar, the Doppler effect, and optical heterodyning. We have chosen a LDDM as our basic system, not only because of its high resolution (2 nm typically) and fast object speed (2 m/s), but also because of its unique performance independent of polarization, which provides the convenience to create a novel multiple-reflection-based optical design to attain sub-100-pm linear resolution.

In the self-aligning multiple-reflection optical design for the LDDM system, the heterodyning detector is housed coaxially inside the frequency-stabilized laser source. Instead of a typical single reflection on the moving target, the laser beam is reflected back and forth twelve times between the fixed base and the moving target as shown in Fig.17 [17,19]. The laser beam, which is reflected back to the heterodyning detector, is frequency-shifted by the movement of the moving target relative to the fixed base. With same LDDM laser source and detector electronics, this optical path provides twelve times greater resolution for the linear displacement measurement and encoding. A 0.03 nm resolution was reached by the prototype LDLE system recently [17].

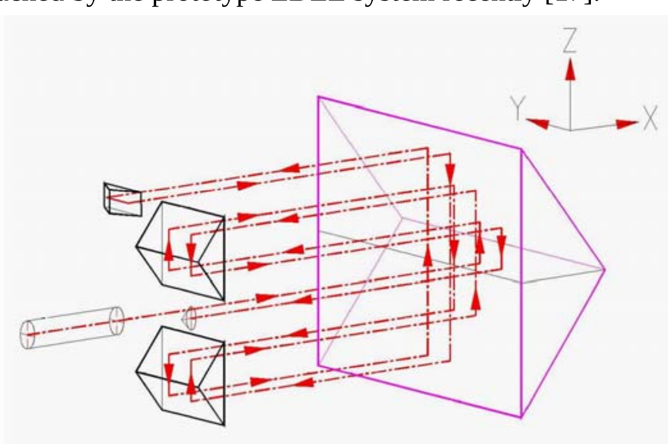

Fig. 17. Schematic of the the self-aligning multiple-reflection optical design. With the same LDDM laser source and detector electronics, this optical path provides twelve times greater resolution for the linear displacement measurement and encoding.

5.2. High-stiffness weak-link mechanism for linear motion reduction

Using the same technique described in section 3.3, we have developed a novel stage using a high-stiffness weak-link mechanism to perform linear motion closed-loop control at the sub-100-pm level with micron-level travel range. The structure consists of four groups of overconstrained weak-link parallelogram mechanisms made with lithography techniques as shown in Fig. 18.

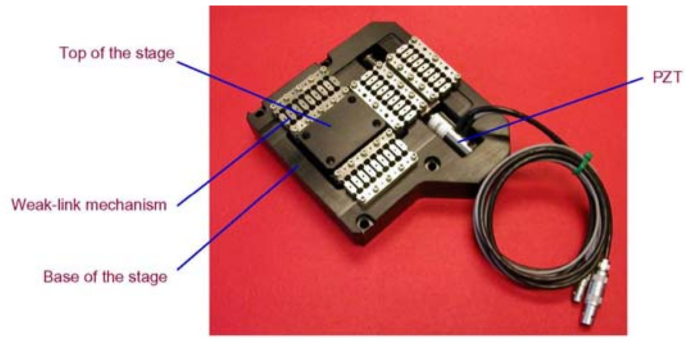

Fig. 18. Photograph of the high-stiffness weak-link linear motion reduction mechanism.

We have tested the sensitivity of the weak-link linear motion reduction mechanism with a laser Doppler
linear encoder. During the test, a Physik Instrumente PI-841 PZT actuator with E-501.10 amplifier [21] was used for input motion control. Driving sensitivity better than 0.03 nm was demonstrated with this weak-link linear-motion-reduction mechanism with a 1-micron travel range.

5.3. A one-dimensional linear actuator system with subnanometer closed-loop control resolution and centimeters travel range

A one-dimensional linear actuator system based on the above high-stiffness weak-link technique andLDDM with multiple-reflection optics has been tested. Figure 19 shows a photograph of the one dimensional laser Doppler linear actuator (LDLA) system for an atomic force microscope. In this coarse/fine closed-loop control setup, a PZT-driven motion-reduction mechanism was mounted on the top of a DC-motor-driven stage to drive the motion object (in this example, a sample holder for an atomic-force microscope). A laser Doppler displacement meter with an optical resolution extension assembly was used to measure the sample holder motion in the 25-mm range with sub-100-pm resolution. The LDDM position signal is fed back through a system-control computer to control the PZT. The PZT drove the motion-reduction mechanism with subangstrom resolution to stabilize the motion. The system control computer also synchronized the stage position and PZT feedback lock-in point with the LDDM position signal [17].

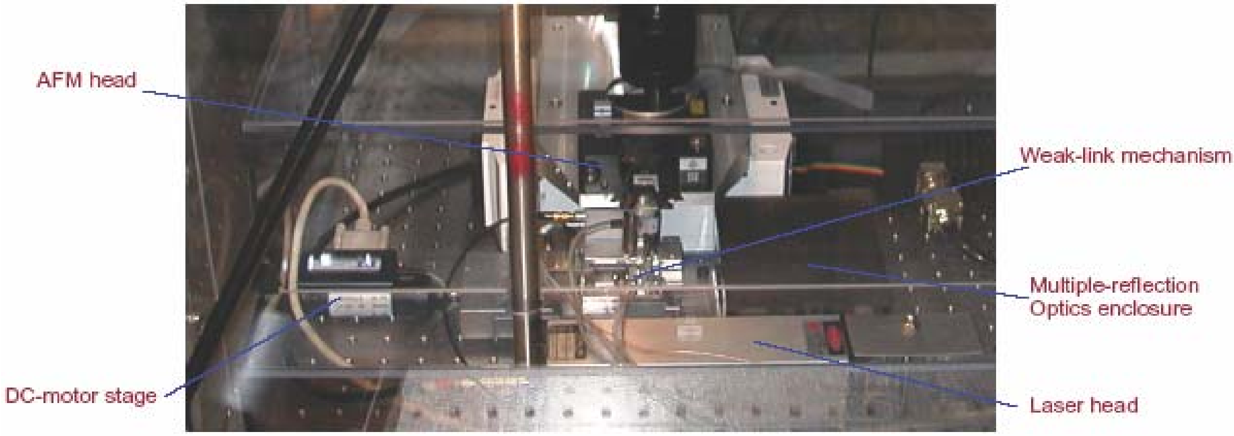

Fig. 19. Photograph of the one-dimensional laser Doppler linear actuator system for an atomic force microscope.

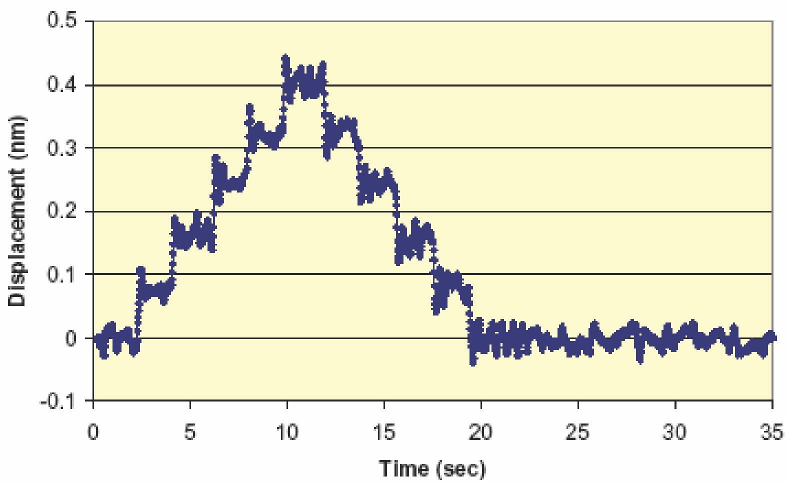

Fig. 20. Resolution test of the one-dimensional laser Doppler linear actuator closed-loop control system. A series of 80-pm steps were demonstrated.

5.4. Design of multiaxis stages with differential measurement capability for an x-ray scanning nanoprobe

A hard x-ray nanoprobe has been proposed as the centerpiece of the x-ray characterization facilities at the APS for the proposed Center for Nanoscale Materials (CNM) to be established at Argonne National Laboratory [22]. This new probe will cover a photon energy range of 3-30 keV. The working distance between the nanofocusing optics and the sample will typically be in the range of 10-30 mm [13]. A dedicated set of source, beamline, and optics will be used to avoid compromising the capabilities of the nanoprobe [23]. This unique instrument will offer diverse capabilities in studying nanomaterials and nanostructures.

We have developed a prototype instrument with a novel LDDM-based scanning stage system. The system consists of nine DC-motor-driven stages, four picomotor-driven stages [24], and two PZT-driven stages. An APS-designed custom-built laser Doppler displacement meter system provides two-dimensional differential displacement measurements with subnanometer resolution between the zone-plate x-ray optics and the sample holder. Also included is the alignment and stable positioning of two zone plates stacked in optical near-field for increasing the focusing efficiency [25]. The entire scanning system was designed with high stiffness, high repeatability, low drift, flexible scanning schemes, and the possibility of fast feedback for differential motion. Figure 21 is a photograph of the prototype scanning stage system for x-ray nanoprobe development.

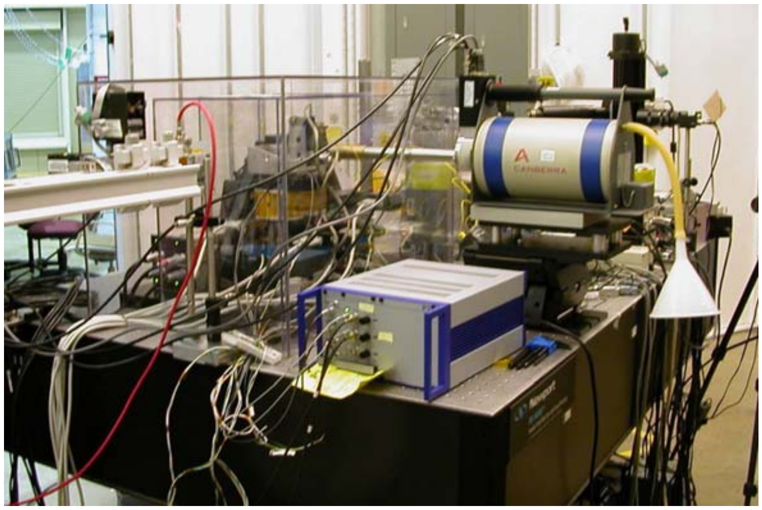

Figure 21: Photograph of the prototype scanning stage system for x-ray nanoprobe at the APS 8-ID-E station

We started the x-ray nanoprobe prototype online commissioning in August 2003. Figure 22 shows an active vibration control test with the prototype system. During this test, the closed-loop control system performed a damping action to a single external mechanical disturbance (an 80-kg mass dropped to the floor from a 0.2-m height at a distance of 3 m). A series of 1-nm and 3-nm differential vertical and horizontal displacement steps (with zoneplate holder and sample holder 5-cm apart) have been demonstrated with closed-loop control as shown in Fig. 23. We are continuing to work on the optimization of the prototype system's dynamic performance.

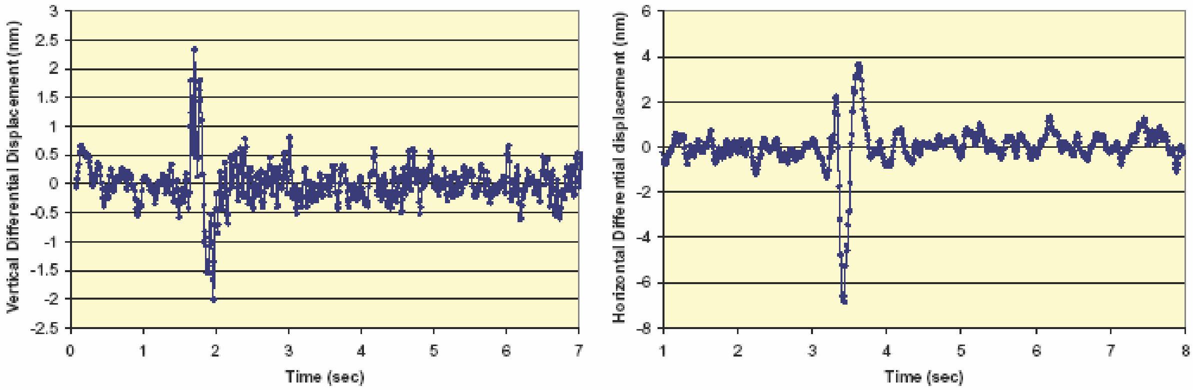

Fig. 22. Active vibration control test for the prototype scanning stage system for x-ray nanoprobe at the APS 8-ID-E station, horizontal: left side; vertical: right side. Vibration source: an 80-kg mass dropped to the floor from 0.2-m height at a distance of 3 m.

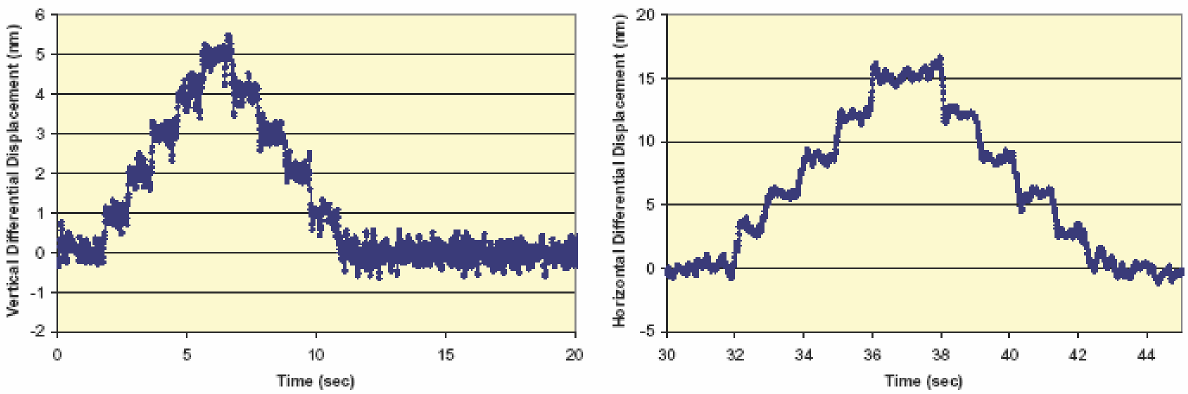

Fig. 23. Closed-loop differential displacement test for the prototype scanning stage system for x-ray nanoprobe at the APS 8-ID-E station, horizontal: left side; vertical: right side.

6. Summary

This paper presented an overview of micro- and nano-positioning design for synchrotron radiation instrumentation applications. The topics include precision positioning devices for synchrotron radiation optics and instrumentation supporting structures. Development of in-vacuum positioning devices and nano-positioning devices are also discussed in this paper. Most of the design examples are selected from APS operational beamline and experimental station components. Limited by the available time and effort, many excellent customized positioning device designs, such as the hexapods developed at ESRF, kinematic couplings developed at Swiss Light Source, and the x-ray microscope scanning stages developed at Advanced Light Source, are not included.

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