# High Precision Positioning Mechanisms for a Hard X-ray Nanoprobe Instrument

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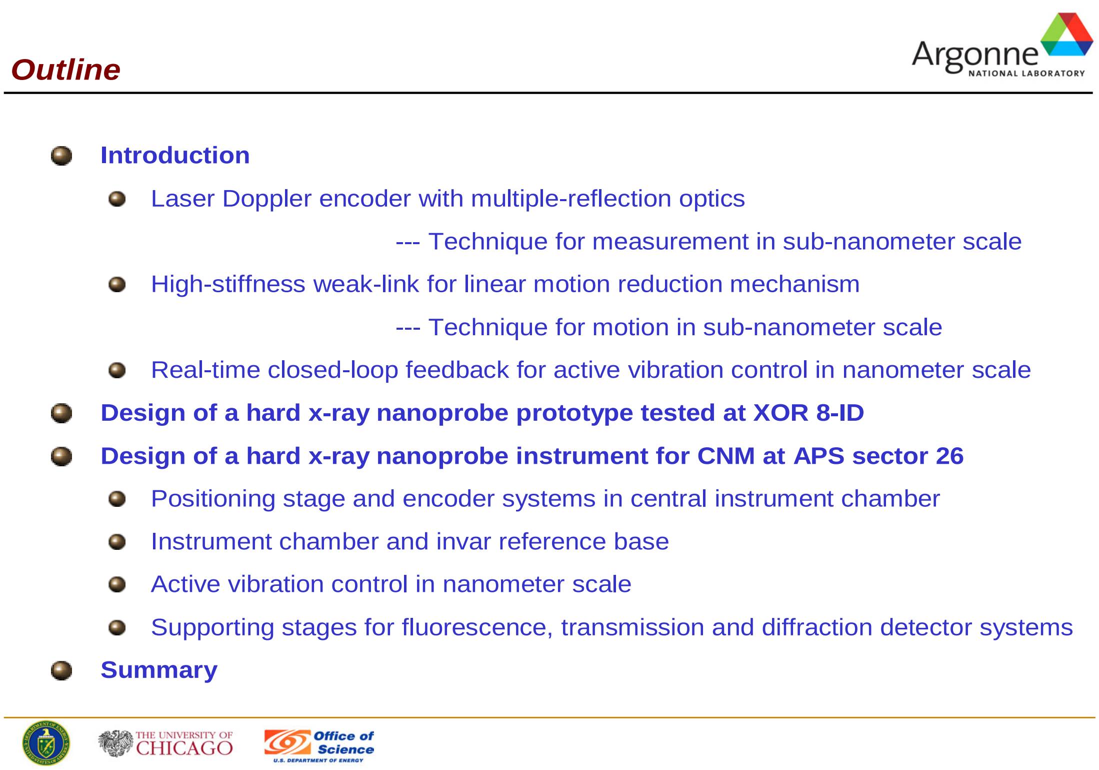
## Abstract

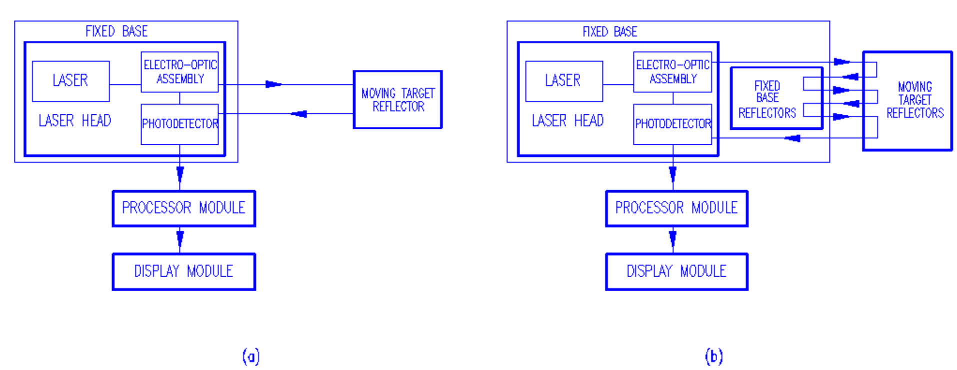
A hard x-ray nanoprobe beamline is being developed at the Advanced Photon Source (APS). The beamline will house a hard x-ray nanoprobe instrument, one of the centerpieces of the characterization facilities of the Center for Nanoscale Materials (CNM) at Argonne National Laboratory (ANL). The nanoprobe instrument will operate with photon energies between 3 keV and 30 keV with 30 nm special resolution initially. Imaging and spectroscopy at this resolution level require staging of x-ray optics and specimens with a mechanical repeatability of better than 10 nm [1].

The instrument will combine a scanning probe mode with a full-field transmission mode. It uses x-ray fluorescence for trace-element mapping and spectroscopy; x-ray diffraction to obtain local structural information such as crystallographic phase, strain texture, and x-ray transmission in phase; and absorption to image internal structures of complex devices.

The high-precision positioning mechanisms for the nanoprobe presented here consist of the following major component groups: a granite base with vibration isolators, an optomechanical instrument vacuum chamber, a robotic detector manipulator for microdiffraction, an in situ optical microscope, and a translation-stage system for a transmission imaging detector [2]. Precision positioning mechanisms for a differential scanning stage system with active vibration control in nanometer scale are also presented in this paper.



## *Laser Doppler encoder with multiple-reflection optics*

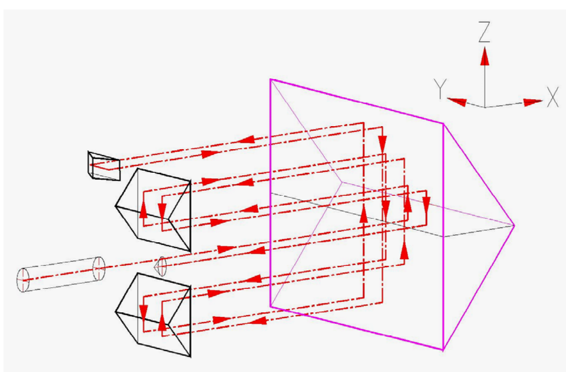



Since 1998 a prototype laser Doppler linear encoder (LDLE) with multiple reflections has been under development at the APS. With a customized commercial laser Doppler displacement meter (LDDM), this novel linear encoder achieved sub-100-pm sensitivity in a 300-mm measuring range. The LDDM is based on 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.



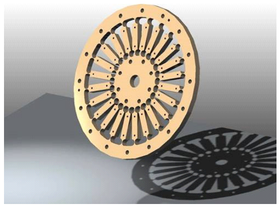


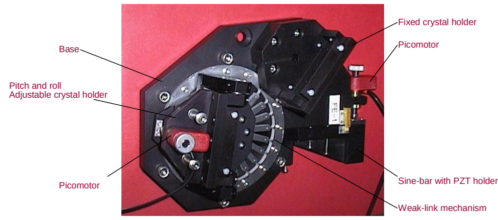
## *Laser Doppler encoder with multiple-reflection optics*




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. 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 LDDM system recently.

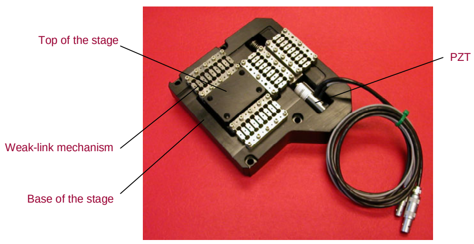
## *Weak-link mechanism for high-energy-resolution x-ray monochromator*





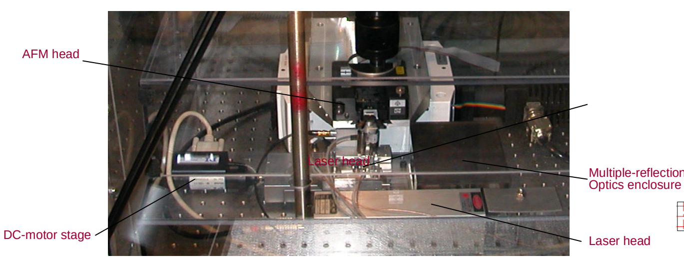

Unlike traditional kinematic linear spring mechanisms, the overconstrained weak-link mechanism provides much higher structural stiffness and stability. Using a laminar structure configured and manufactured by chemical etching and lithography techniques, we are able to design and build a planar-shape, high-stiffness, high-precision weak-link mechanism.

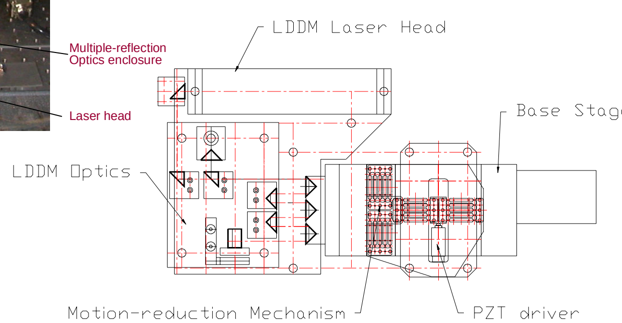
The precision of modern photochemical machining processes using lithography techniques makes it possible to construct a strain-free (or strain-limited) overconstrained mechanism on thin metal sheets. By stacking these thin-metal weak-link sheets with alignment pins, we can construct a solid complex weak-link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




Using the same technique described in the section for the weak-link mechanism for a high-energy- resolution monochromator, 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. Driving sensitivity better than 30 pm was demonstrated with this weak-link linear-motion-reduction mechanism with a 1-micron travel range.

## *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 and LDDM with multiple-reflection optics has been tested. This photo shows 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 one-dimensional linear actuator system with subnanometer closed-loop control resolution and centimeters travel range*

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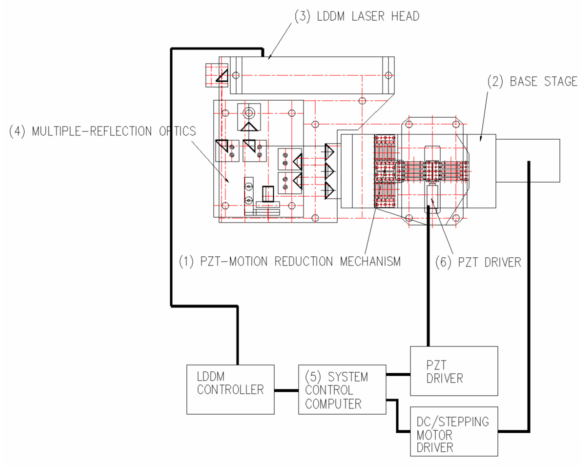


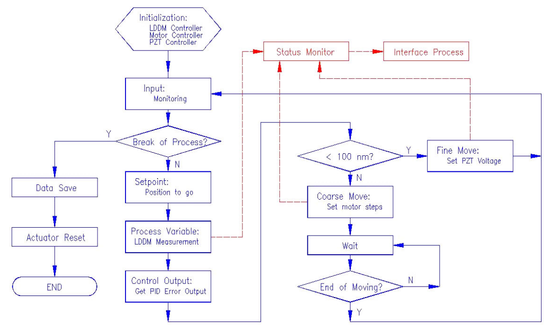


A laser Doppler displacement meter with an optical resolution extension assembly was used to measure the sample holder motion in the 25-mm range with sub-100-pm resolution. The LDDM position signal is fed back through a system-control computer to control the PZT. The PZT drove the motion-reduction mechanism with sub-100-pm 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.

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

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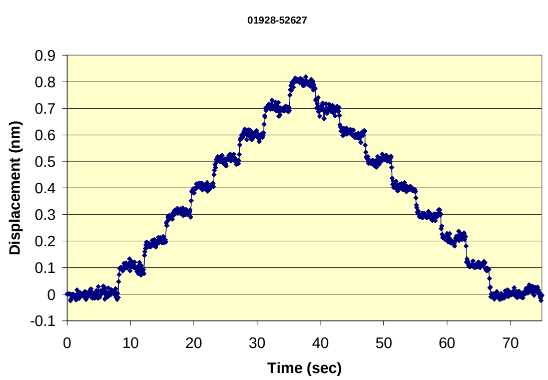
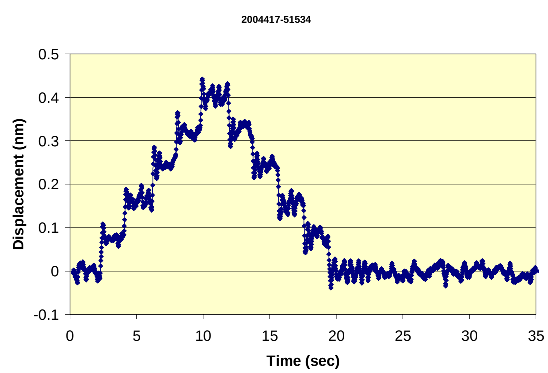
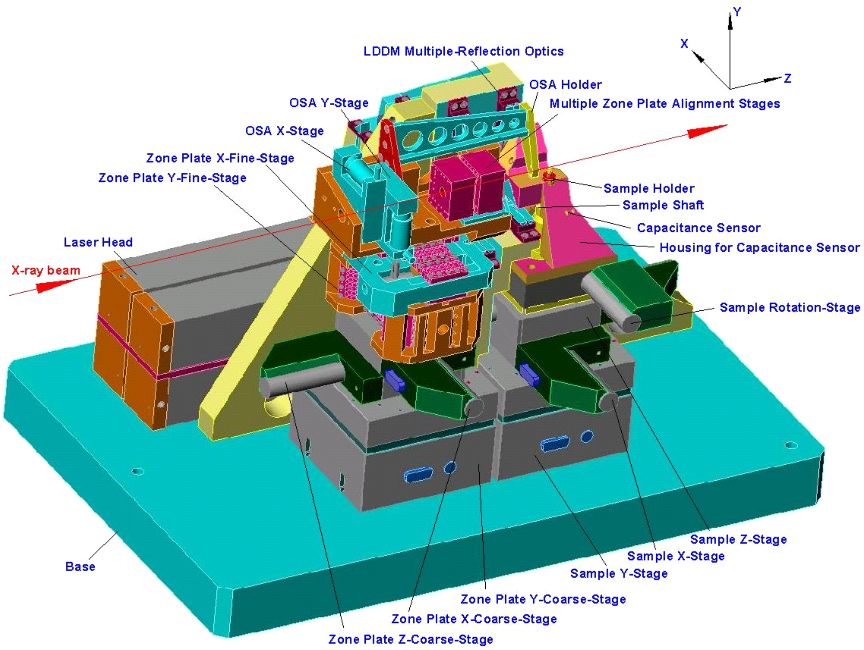



Resolution test of the one-dimensional laser Doppler linear actuator closed-loop control system. A series of 100-pm (left side) and 80-pm (right side) steps have been demonstrated.

## Design of an X-ray Nanoprobe Prototype

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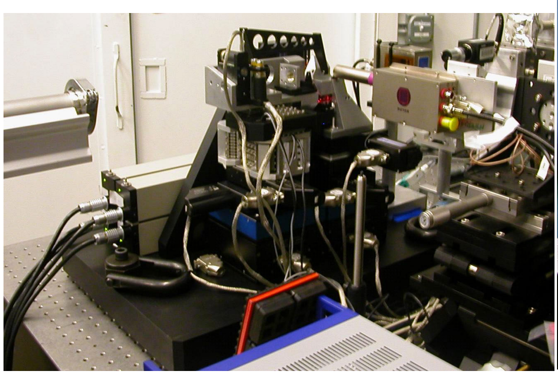
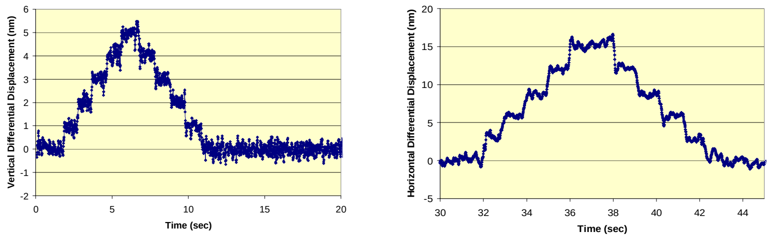
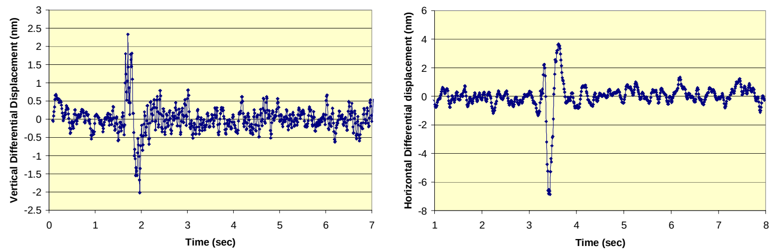


We started the x-ray nanoprobe prototype online commissioning in August 2003. These are photographs of the prototype at the APS 8-ID-E experimental station (left) and in a test laboratory (right).

## *Design of an x-ray nanoprobe prototype*




Closed-loop differential displacement test for the prototype scanning stage system for the x-ray nanoprobe at the APS 8-ID-E station, horizontal: left side; vertical: right side. A series of 1-nm and 3-nm differential vertical and horizontal displacement steps (between zone-plate holder and sample holder) have been demonstrated with closed-loop control.




Active vibration control test for the prototype scanning stage system for the x-ray nanoprobe at the APS 8-ID-E station, vertical: left side; horizontal: right side. 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).



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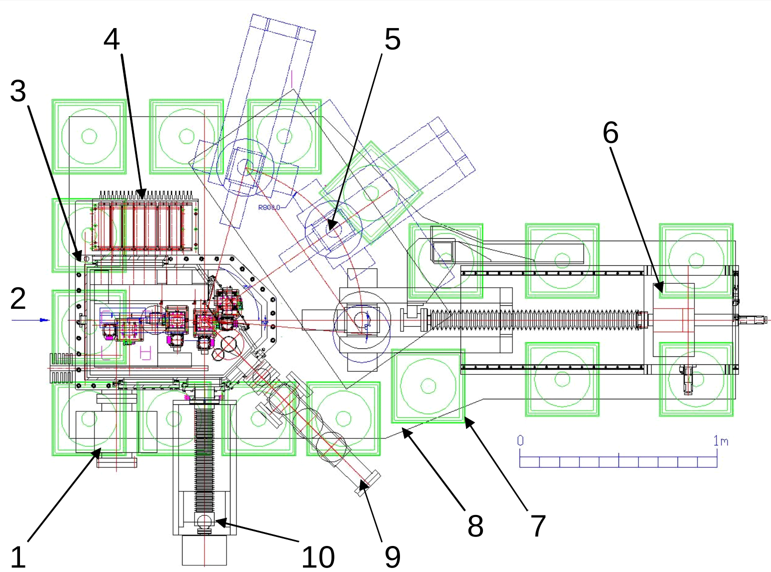
## *General layout design*




Top view of the hard x-ray nanoprobe instrument. (1) Ion pump; (2) Incident beam; (3) Instrument Chamber; (4) Laser head for LDDM; (5) Diffraction detector; (6) Transmission imaging detector; (7) Isolators below base; (8) Granite base; (9) Airlock for specimen exchange; (10) Fluorescence detector.

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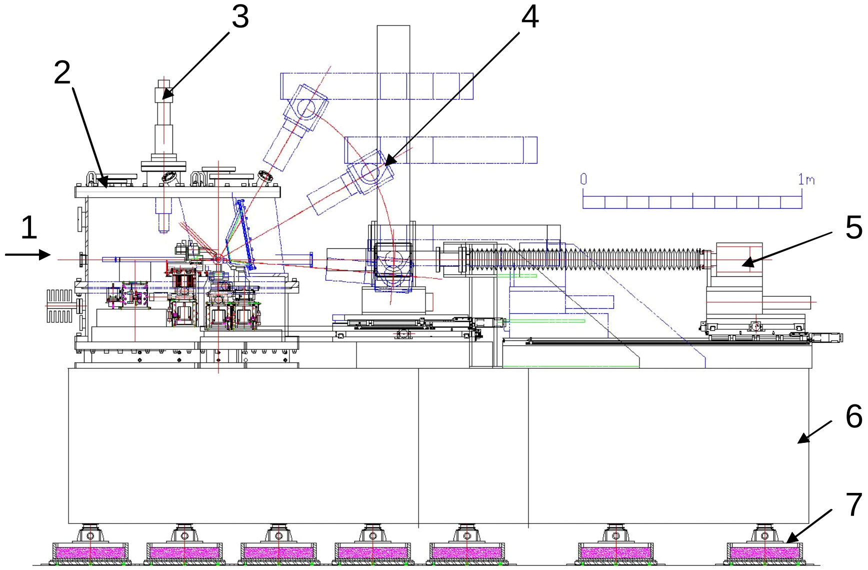
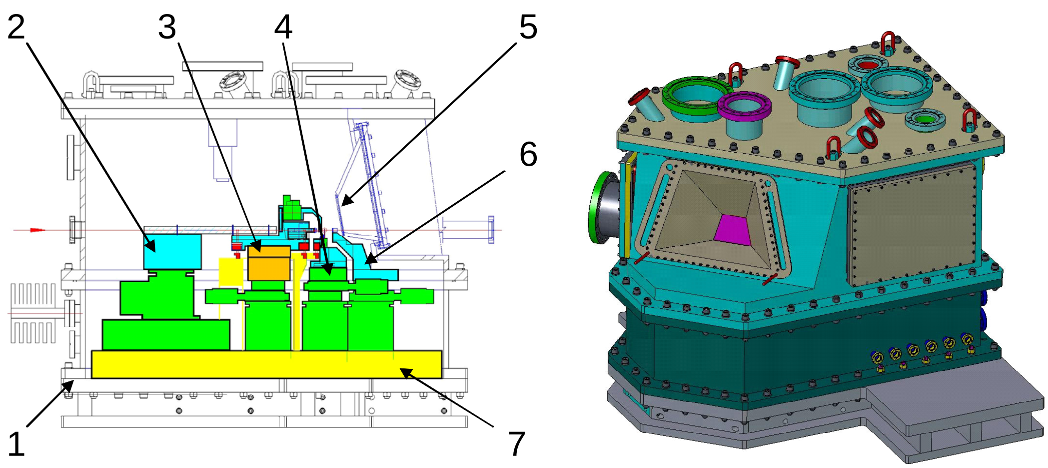
## *General layout design*



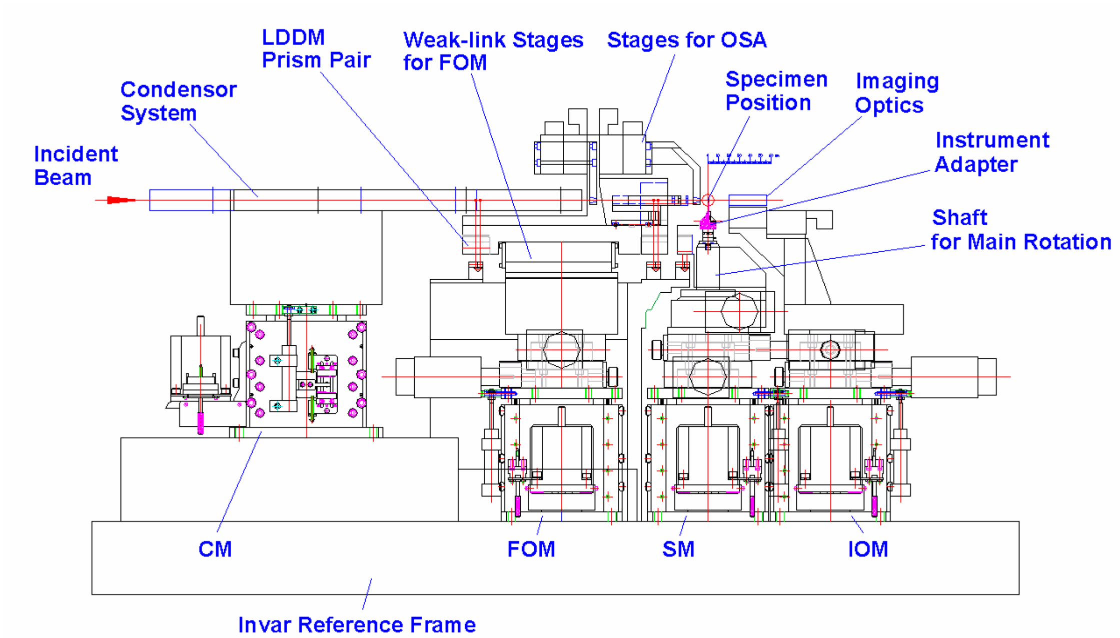

Side view of the hard x-ray nanoprobe instrument. (1) Incident beam; (2) Instrument chamber; (3) Optical microscope; (4) Diffraction detector; (5) Transmission imaging detector; (6) Granite base; (7) Isolators.

## *Positioning stage and encoder systems in central instrument chamber*

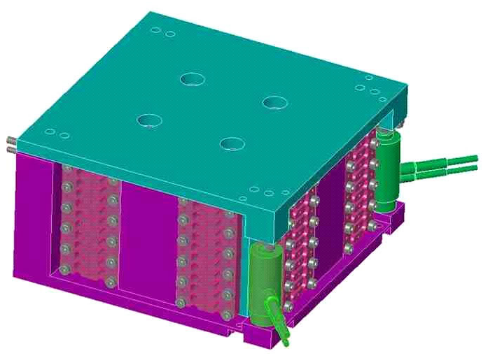



Left: A schematic side view of the nanoprobe instrument chamber. (1) Vacuum chamber; (2) CM; (3) FOM; (4) SM; (5) Beryllium window; (6) IOM; (7) Invar reference base. Right: A 3-D model of the nanoprobe instrument chamber.

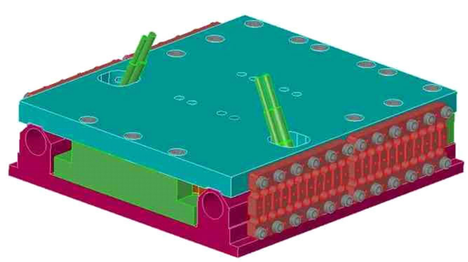
## *Positioning stage and encoder systems in central instrument chamber*




## *Scanning stages for focusing optics module*



Vertical Flexure stage

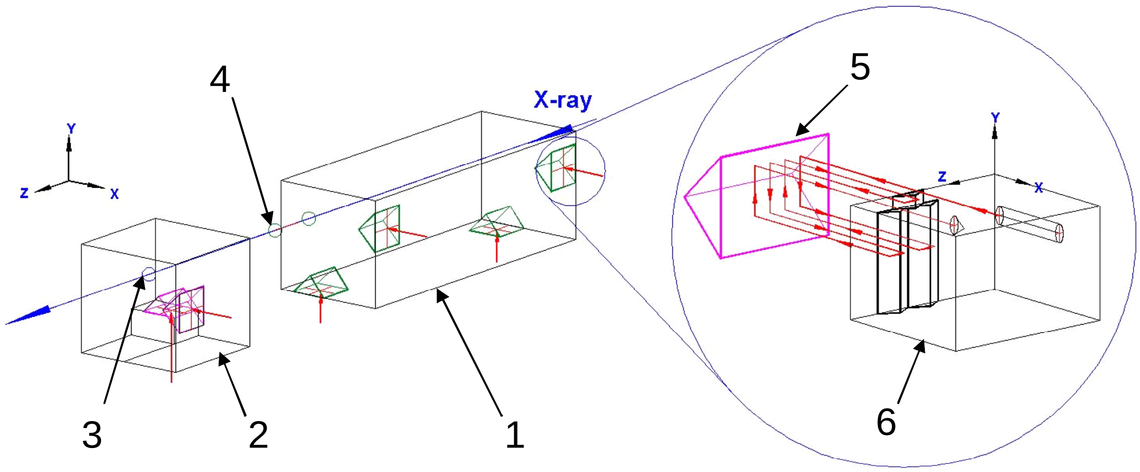


Horizontal Flexure stage

To optimize the motion straightness of trajectory, three piezo actuators are used in parallel on the vertical flexure stage. Two piezo actuators are used on the horizontal stage. This design provides more than 10x higher structural stiffness than commercial 2D stages (such as PI-500), and, due to the composite nature of the flexure hinges, better vibration damping.

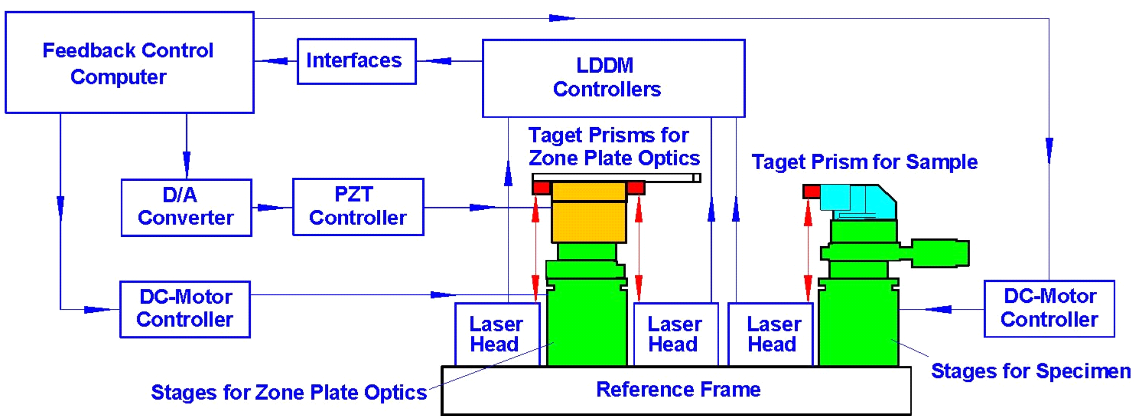
The resolution of the stage is 0.3 nm with a travel range of 15 microns. Physik Instrumente™ PZT actuators with strain-gauge sensor servo-control modules were used to drive both high- and medium-resolution weak-link stages.

# Laser Doppler encoders for differential 2D positioning and active vibration control




Schematic of the six-LDDM encoder system for the two-dimensional differential position encoding between the FOM and SM. (1) Prism holder for zone-plate optics; (2) Prism holder for sample stage; (3) Sample location; (4) Zone-plate optics locations; (5) Prism on the stage; (6) Prism group on the reference frame.


# Laser Doppler encoders for differential 2D positioning and active vibration control


Schematic of differential positioning feedback control in the vertical (Y) direction. For the differential feedback positioning control in the vertical (Y) direction, two LDDMs are applied to the FOM and SM in the Y direction. Since the reference frame defines the coordinate system of the nanoprobe, all positions are measured with respect to this frame. To perform a differential measurement between the stage groups for FOM and SM in the Y direction, a DSP-based feedback control computer is used as a control console to collect the position information from the three LDDMs with a positioning update rate of 937 kHz. The DSP computes the position differences between the two stage groups and determines the discrepancy between the actual and desired differential position between the zone-plate optics and sample, and feeds back differential position-correction signals through a proportional-integral-derivative (PID) loop to the PZT-driven weak-link stage on the FOM. Differential scanning motion can be activated by controlling the desired differential position value. In the case of large-range scanning activity, a relay mechanism is implemented into the control software to ensure a smooth transition between the PZT-driven weak-link fine stage and the DC-motor-driven coarse translation stage.

## *SUMMARY*

This presentation provides a overall view of the precision engineering approach for a design for the CNM Hard x-ray Nanoprobe instrument based on a combined scanning probe/full-field transmission instrument.

The engineering design presented takes into consideration the experience gained from developing a high-precision staging system for the CNM Early User Instrument. It builds on a modified mechanical design of the optics staging, a modified layout of the encoder system, and a different strategy for instrument controls.

### *Acknowledgments*

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[3] LDDM is a trademark of the Optodyne Inc., 1180 Mahalo Place, Compton, CA 90220, U.S.A.

[4] U.S. Patent granted No. 5,896,200, D. Shu, 1999.

[5] U.S. Patent granted No. 6,822,733, D. Shu, 2004.

[6] D. Shu, T. S. Toellner, and E. E. Alp, Nucl. Instrum. Methods A 467-468, 771-774 (2001).

[7] U.S. Patent granted No. 6,607,840, D. Shu, T. S. Toellner, and E. E. Alp, 2003.

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[9] D. Shu, J. Maser, B. Lai, S. Vogt, M. Holt, C. Preissner, A. Smolyanitskiy, R. Winarski, and G. B. Stephenson, High Precision Positioning Mechanisms for a Hard X-ray Nanoprobe Instrument, to be published in the AIP Proceedings of SRI 2006.

[10] D. Shu, T. S. Toellner, E. E. Alp, J. Maser, J. Ilavsky, S. D. Shastri, P. L. Lee, S. Narayanan, and G. G. Long, Applications of Laminar Weak-Link Mechanisms for Ultraprecision Synchrotron Radiation Instruments, to be published in the AIP Proceedings of SRI 2006.