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D. Shu, E. Nazaretski

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Optomechanical Design of a Multilayer Laue Lens Test Bed for 10-nm Focusing of Hard X-rays

Deming Shu[1], Evgeny Nazaretski[2], Jungdae Kim[2a], Hanfei Yan[2], Kenneth Lauer[2], Brian Mullany[2], Dennis Kuhne[2], Jörg Maser[1], and Yong S. Chu[2]

[1]Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA
[2]NSLS-II, Brookhaven National Laboratory, Upton, NY 11973, USA

Email: shu@aps.anl.gov

Abstract. A multilayer Laue lens (MLL) test bed was designed at the Argonne National Laboratory for the National Synchrotron Light Source-II (NSLS-II) project at Brookhaven National Laboratory. Argonne and Brookhaven scientists and engineers collaborated to carry out this work in order to achieve NSLS-II's R&D goals of 10-nm focusing of hard x-rays. The test-bed design was based on the experience gained from the Argonne nanopositioning system designed for the CNM/APS hard x-ray nanoprobe project and an MLL test bed at Advanced Photon Source (APS) beamline 26-ID [1-3]. Optomechanical design of the MLL test bed, as well as the preliminary test results for the alignment apparatus and sample base stages' mechanical vibration performances are presented in this paper.

1. Introduction

In 2006, H. C. Kang et al. reported on the development of hard x-ray nanofocusing with linear multilayer Laue lenses (MLLs). Using tilted partial MLL structures, a one-dimensional focus as small as 16 nm with efficiencies up to 44% was demonstrated using synchrotron x-rays with a photon energy of 19.5 keV [1]. These MLLs are intrinsically suitable for focusing hard x-rays to a few nanometers.

To perform ideal 2D focusing, the first prototype of a precision multidimensional alignment apparatus was designed and constructed for an MLL test bed at the APS and tested at beamline 26-ID in 2008 [2,3]. With this test bed, MLL optics demonstrated the focusing capability of hard x-rays to a 2-D focus of 25 nm horizontal x 27 nm vertical FWHM at a photon energy of 12 keV, and of 25 nm horizontal x 40 nm vertical FWHM at a photon energy of 19.52 keV [4].

In 2010, a second MLL test bed was designed at Argonne National Laboratory (ANL) for the National Synchrotron Light Source-II (NSLS-II) nanopositioning development project at Brookhaven National Laboratory (BNL). This work was carried out as collaboration between Argonne and Brookhaven scientists and engineers, in an effort to achieve NSLS-II's R&D goals of achieving 10-nm focusing of hard x-rays. The second MLL test bed has been installed, and commissioning began at a long imaging beamline experimental station (I13L) at the Diamond Light Source (DLS), UK, in April 2012. It will be used as an initial platform for further nanofocusing developments in collaboration with the DLS staff. Figure 1 shows a 3-D model for the MLL test bed for 10-nm focusing of hard x-rays. It includes a precision MLL multidimensional alignment apparatus (1) and a sample stages group (2). Optomechanical design of the second MLL test bed for NSLS-II is presented in this paper.

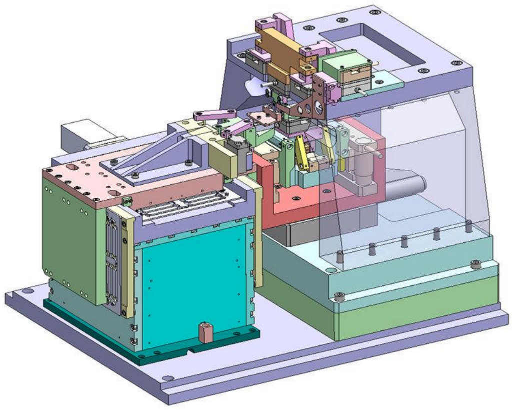


Figure 1. A 3-D model for the MLL test bed for 10-nm focusing of hard x-rays. It includes a precision MLL multidimensional alignment apparatus and a sample stages group.

2. Design of the multidimensional alignment apparatus for MLL 2-D focusing

To perform 2-D focusing, the MLL test bed needs to provide capability to align precisely two MLLs with respect to each other in a total of eight degrees of freedom. Figure 2 (left) shows a schematic diagram of precision motions required for alignment of two MLL sections for a 2-D x-ray focusing. As shown in Figure 2 (right), the multidimensional alignment apparatus for the second MLL test bed has the same mechanical design as the first one [3]. To minimize the thermal energy dissipation on the alignment apparatus, the PI^{TM} M-663 stages applied for the second MLL test bed are customized to relocate their encoder interpolators from the stages to the controllers.

In the alignment apparatus, the upstream MLL lens is mounted on the lower group of stages, which provides precision positioning in five degrees of freedom that include three translational and two angular adjustments as shown in Figure 3 (left). The downstream MLL lens is mounted on the upper group of stages that provide two translational and one rotational degree of motion as shown in Figure 3 (right). Table 1 summarizes the design specification for each adjustment [2].

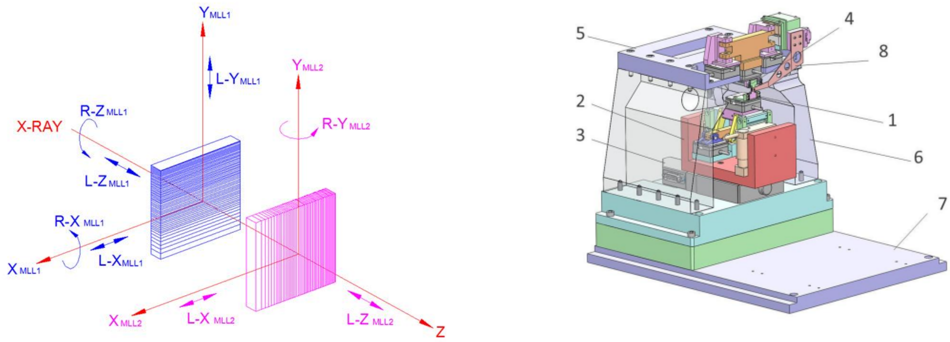
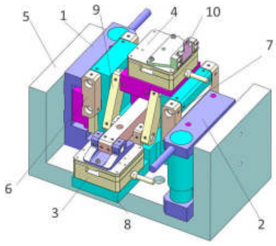


Figure 2. Left: Schematic diagram of precision motions required for alignment of two MLL sections for a 2-D x-ray focusing test-bed [2]. Right:: A 3-D model of the multidimensional alignment apparatus, which includes: (1) upstream MLL, (2) nested flexural bearing structure, (3) PI^{TM} M-126 motorized horizontal linear stage, (4) downstream MLL, (5) upper stages group, (6) support structure, (7) base plate, and (8) OSA and stages.

TABLE 1. Design specifications for alignment motions for a 2-D x-ray focusing prototype with two MLLs in a crossed configuration.

Motion	Driver	Resolution	Travel Range
L-X_{MLL1}	Ultrasonic piezomotor with linear optical encoder	0.1 micron	15 mm
L-Y_{MLL1}	DC motor with gearhead and shaft optical encoder	0.1 micron	5 mm
L-Z_{MLL1}	Stepping motor with gearhead and shaft optical encoder	1 micron	25 mm
R-X_{MLL1}	Differential driven DC motor with gearhead and shaft optical encoder	0.4 arcsec	3 degrees
R-Z_{MLL1}	Ultrasonic piezomotor with linear optical encoder	0.4 arcsec	3 degrees
L-X_{MLL2}	Ultrasonic piezomotor with linear optical encoder	0.1 micron	15 mm
L-Z_{MLL2}	Dual ultrasonic piezomotor with linear optical encoder	0.1 micron	15 mm
R-X_{MLL2}	Differential driven ultrasonic piezomotor with linear optical encoder	0.3 arcsec	3 degrees



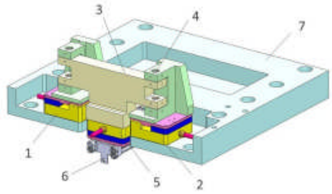


Figure 3. Left: A 3-D model of the nested flexural bearing structure for angular adjustments along the axes of XMLL1 and ZMLL1. The nested flexural bearing structure is operated by two PI^{TM} M-110 motorized linear stages (1) and (2), and two PI^{TM} M-663 PZT-driven linear stages (3) and (4). The linear stages (1) and (2) are mounted on a U-shaped base frame (5). Cooperated with the outer flexural bearing structures (6) and (7), linear stages (1) and (2) provide linear positioning in the Y direction and tilting adjustment around the X-axis for another U-shaped frame (8), which is the base for a 4–bar flexural bearing structure (9) nested in the outer flexural structure. The 4–bar flexural bearing structure is operated by the PZT-driven linear stage (3) to provide a precise angular positioning around the Z-axis. The linear stage (4), mounted on the top of the 4–bar flexural bearing structure, aligns the upstream MLL (10) in the X direction. Right: A 3-D model of the upper stages group, which includes three PI^{TM} M-663 PZT-driven linear stages. A pair of linear stages (1) and (2) drive a carriage (3) through a set of flexural bearings (4) to perform linear positioning in the Z-axis direction with tilting adjustment around the Y-axis. The linear stage (5) provides the alignment in the X direction for the downstream MLL (6).

3. The flexural sample base stages for the MLL test bed

As shown in Figure 1, the sample stages group (2) for the MLL test bed provides one angular and three linear scanning capabilities for analyzing the x-ray focal spot at the location of a specimen. As in the flexural sample base stages T8-31/32 developed in 2008 at APS [5,6], the design of the vertical and horizontal flexural stages T8-33/34 for the NSLS-II sample stages group are based on experiences from developing high-stiffness laminar overconstrained weak-link mechanisms for ultrahigh-resolution monochromators and nanopositioning stages at the APS [6,7]. The T8-33/34 linear stages are guided with the same fishbone-shaped multiple parallelogram weak-link modules used for T8-31/32 [6]. Each of the 2-mm-thick 118 mm x 116 mm weak-link modules is a bound laminar structure with eight thin-metal weak-link sheets configured and manufactured by chemical etching and lithography techniques. The finite element simulation for a 1.61-mm displacement of the carriage shows that, while a 17-N force is applied on the carriage, the maximum Von Mises stress is 974 MPa, which is about 81% of the tensile yield strength of the stainless steel 17-7 PH. The simulation shows that, if the carriage is driven by the same level of push-pull force, the weak-link linear stage will have a travel range of 3.22 mm.

The T8-31 and T8-32 flexural stages were driven by PI Nexline^{TM} N-214 and N-110 PZT actuators. To extend the stage driving force and load capacity, T8-33 and T8-34 stages were designed to be driven by PI Nexline^{TM} N-216 and N-111 PZT actuators with optional high vacuum compatibility as shown in Figure 4 (left). Two sets of T8-33/34 stages were constructed in 2010, one for the APS Sector 2 hard x-ray microscope station with high vacuum compatibility, and one for the NSLS-II MLL test bed. To improve closed-loop positioning repeatability, external capacitive or optical sensors were added on the T8-33/34 stages for the NSLS-II MLL test bed as shown in Figure 4 (right).

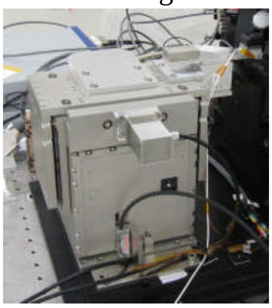
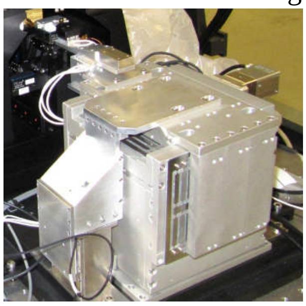



Figure 4. Left: A photograph of the sample stages group. Right: A photograph of the sample stages group with MicroSenceTM capacitive position sensors. In both photographs, the original vertical axis tip-tilting stage and associated SmarAct^{TM} SLC-1720-S linear stage as shown in Figure 1 are replaced with a Pizesystem Jena^{TM} Tritor 38-SG scanner and a SLC-1720-S linear stage for high-speed sample scanning applications.

4. Preliminary test and summary

To ensure that the mechanical structural stability of the MLL test bed is suitable for 10-nm focusing of hard x-rays, vibration tests were performed for both the alignment apparatus and the sample base stages. Vibration spectra were measured with PCB^{TM} 356 and 393 accelerometers for the alignment apparatus. Preliminary measurement on the top of the upstream MLL stage showed that the apparatus does not amplify the vibration from the mounting base. Although the sensor used on the top of the upstream MLL stage is a compact sensor (PCB-356) with a noise level higher than 10 nm in the frequency range below 8 Hz, we did not observe any peak above its noise floor [2].

Preliminary vibration test using Vibra-Metrics^{TM} 1030 accelerometers demonstrated that the T8-33 vertical linear weak-link stage with 8-kg load does not amplify the vibration from the mounting base, similar to the T8-31 stage test [5]. Also like the T8-31 stage, the T8-33 vertical linear weak-link linear stage has demonstrated high tilting stiffness and high straightness of trajectory with nanometer-level positioning sensitivity. Its tilting stiffness is better than many commercial motor-driven linear bearing-guiding vertical stages with similar structure sizes, and the amount of the tilt is repeatable within 1-μrad range over the stage's full 3 mm travel range.

The second MLL test bed has been installed, and commissioning began at a long imaging beamline experimental station (I13L) at the DLS, UK, in April 2012, as shown in Figure 5.

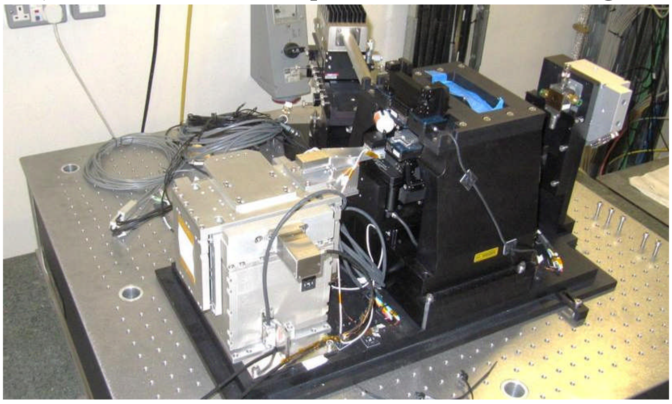


Figure 5. A photograph of the MLL test bed for 10-nm focusing of hard x-rays to be commissioned at a long imaging beamline experimental station (I13L) at the Diamond Light Source (DLS), UK. It will be used as an initial platform for further nanofocusing developments in collaboration with the DLS staff.

5. References

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[a] Jungdae Kim's current address "Department of Physics, University of Ulsan,Ulsan 680-749, Korea".

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