MECHANICAL DESIGN AND PRACTICE OF ARTIFICIAL CHANNEL-CUT CRYSTAL STAGES FOR THE BONSE-HART USAXS INSTRUMENT WITH 10-NANORADIAN-SCALE RESOLUTION AND STABILITY

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INTRODUCTION

Small-angle X-ray scattering (SAXS) is a nondestructive measurement technique in which the elastic scattering of X-rays from inhomogeneities within a sample is recorded at low scattering angles. The typical range of scattering angles in a pinhole SAXS camera delivers structural information on lengths between 1 nm and 100 nm. To resolve microstructures with larger dimensions, however, the smaller angles available with ultra-small angle X-ray scattering (USAXS) are required.

The Advanced Photon Source (APS) USAXS instrument is located at X-ray Operations and Research (XOR) Sector 32, where it receives photons from an APS undulator x-ray source. The undulator source provides continuous access to X-rays in the energy range from 3.2 to above 80 keV. The photons subsequently pass through a fixed-offset Si (111) monochromator capable of tuning the photon energy between 8 and 35 keV. To reject the unwanted higher-order harmonics, a pair of vertically reflecting flat silicon mirrors follow the monochromator. The mirrors have three stripes, Si, Cr, and Rh, each with a different angular dependence on X-ray energy for total reflection. By means of a simple horizontal translation to select the appropriate reflection stripe, the mirrors reject harmonics for primary photons in the energy range from 8 to 19 keV, which is the operational range of the APS USAXS [1,2].

As shown in Figure 1, the APS USAXS instrument in one-dimensional collimated imaging configuration includes 2D slits, a Si (111 or 220) collimating system, an ion chamber, a sample holder stage, a Si (111 or 220) analyzer system, and a photodiode detector system.

The collimating crystal system and analyzer crystal system are similar, and make use of a design illustrated in Figure 2, where the triangular cut of the first crystal makes it possible to select the number of reflections by translating the crystal pair horizontally with fixed-gap artificial channel-cut crystal geometry.

A windowless ionization chamber after the collimating crystals monitors the X-ray intensity reaching the sample position. The scattering sample is mounted on a standalone stage with two motorized orthogonal translational axes. This allows samples to be attached to a sample-mounting plate and measured in sequential order. Space around the sample stage makes possible the installation of sample environments such as heating stages, flow cells, tensile stages and liquid cells [1].

In this paper we present the mechanical design of the artificial channel-cut crystal stages for the APS USAXS instrument. Finite-element analyses for the laminar weak-link mechanism as well as X-ray test results for the USAXS crystal X-ray optics are also presented.
THE CRYSTAL OPTICS FOR A FIXED-GAP BONSE-HART USAXS INSTRUMENT

Unlike the original and widely adopted design of Bonse and Hart USAXS instruments [3] that used an odd number of reflections from the collimating crystals, the APS USAXS instrument uses an even number of reflections in a nondispersive geometry. A narrow crystal gap, combined with the many reflections, prohibits the direct (uncollimated) beam from reaching the sample.

![Figure 2](image1.png)

**FIGURE 2.** Schematic of the APS USAXS fixed-gap collimating crystals. (a) configuration for four reflections. (b) configuration for two reflections. (c) single reflection configuration for commissioning alignment.

THE ARTIFICIAL CHANNEL-CUT CRYSTAL STAGES

The quality of the crystal surfaces is the key to ensuring that the wings of the instrumental rocking curve are effectively suppressed over the large q range for USAXS data acquisition. To overcome the manufacturing difficulties for a regular channel-cut crystal with small gap and exceptional surface quality, artificial channel-cut crystal stages [4,5] are applied for both collimating crystals and analyzer crystals. The precision and stability of this mechanism allowed us to align or adjust a pair of high-surface-quality crystals to achieve the same performance as that of a single channel-cut crystal, and to ensure the 10-nanoradian-scale alignment resolution and stability required for their variable multiple-reflection X-ray optics in an angular alignment range of near 1 degree.

**Design of the artificial channel-cut crystal stage**

Figure 3 shows a 3D model of the artificial channel-cut crystal stage for the APS USAXS instrument vertically diffracting crystal analyzer system. As shown in this figure, the base plate (2) of the artificial channel-cut crystal stage is mounted on a commercial rotary stage (11) from Aerotech, Inc. [6] via a pair of adapter plates (12,13). The adapter plates provide manual linear alignment capability between the rotary stage and the artificial channel-cut crystal stage.

![Figure 3](image2.png)

**FIGURE 3.** A 3D model of the artificial channel-cut crystal stage for the APS USAXS instrument: crystal analyzer system. (1) high-stiffness, weak-link mechanism module; (2) base plate; (3) sine-bar; (4,5) two silicon single crystals; (6) Picomotor™; (7) Physik Instrumente™ closed-loop controlled PZT; (8) commercial flexure bearing; (9) crystal holder; (10) Picomotor™-driven structure; (11) Aerotech™ rotary stage; (12,13) adapter plates; (14) balancing plate.

There is a pair of stacked thin-metal weak-link modules (1) used in the driving mechanism. The weak-link module is a planar-shaped, high-
stiffness, high-stability mechanism acting as a planar rotary shaft. One set of weak-link mechanisms is mounted on each side of the base plate (2). A sine-bar (3) is installed on the center of the planar rotary shaft for the pitch alignment between the two single crystals (4, 5). Two linear drivers are mounted on the base plate serially to drive the sine-bar. The rough adjustment is performed by a Picomotor™ (6) with a 20- to 30-nm step size. A Physik Instrumente™ closed-loop controlled PZT (7) with strain sensor provides 1-nm resolution for the pitch fine alignment. A pair of commercial flexure bearings (8) mounted on each of the crystal holders (9) and Picomotor™-driven structures (10) to provide the roll alignment for each crystal. To keep the load balanced for the rotary stage (11), a balancing plate (14) is applied on the adapter plate (13). Figures 4 and 5 illustrate the side, top, and rear views of the artificial channel-cut crystal stages.

**FIGURE 4.** A side view of the 3D model of the artificial channel-cut crystal stage for the APS USAXS instrument crystal analyzer system.

**FIGURE 5.** The rear view (left) and top view (right) of the 3D model of the artificial channel-cut crystal stage for the APS USAXS instrument crystal analyzer system.

**The laminar overconstrained weak-link module**

The original laminar overconstrained weak-link module was created to overcome the obstacles encountered in developing a 4-crystal in-line high-resolution hard x-ray monochromator using a nested channel-cut crystal geometry with meV bandpass. The first high-stiffness weak-link mechanism with stacked thin-metal sheets developed for the APS high-energy-resolution beamline 3-ID [4,5]. The precision and stability of this mechanism allowed us to align or adjust an assembly of crystals to achieve the same performance as that of a single channel-cut crystal, so we called it an "artificial channel-cut crystal."

Unlike traditional kinematic linear spring flexure mechanisms, the overconstrained rotary 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 module as shown in Figure 6. The precision of modern photochemical machining processes using lithography techniques makes it possible to construct a strain-limited overconstrained structure from thin metal sheets. By stacking these thin-metal weak-link sheets with alignment fixtures, we can construct a solid, complex, thick weak-link module with reasonable cost [5].

**FIGURE 6.** A finite-element simulation for a wheel-shaped rotary weak-link module. It shows the displacement distribution under a torsion load on the outer ring while the center part is fixed on the base.
As shown in Figures 6 and 7, the overconstrained weak-link module made from 304 stainless steel is capable of performing a +/-0.25 degree rotary elastic displacement with 20% safety margin to the material yield strength. With high-strength materials, such as stainless steel 17-7 ph, the same module will be capable of performing a +/-1 degree rotary elastic displacement with 30% safety margin to its yield strength.

**X-RAY TEST RESULTS AND DISCUSSION**

The APS Bonse-Hart USAXS instrument using artificial channel-cut crystal stages at the APS XOR Sector 32 at Argonne National Laboratory is now operational. It is a fundamental characterization facility that is optimized for the high brilliance and low emittance of an APS undulator source. Its $10^{-4}$ angular and energy resolutions, accurate and repeatable X-ray energy tunability over an operational energy range from 8 to 18 keV, and excellent signal-to-noise ratio support a wide range of tasks, from addressing the fundamental scientific issues in soft matter to characterization of shocked materials.

Figure 8 shows the APS Bonse-Hart USAXS instrument crystal analyzer using artificial channel-cut crystal stages at APS XOR Sector 32. Figure 9 shows an X-ray rocking curve scan using the artificial channel-cut crystal stage with a step size of about 300 nrad.

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**REFERENCES**

[6] Customized ADR-240 stage from Aerotech, Inc. Pittsburgh, PA 15238, USA