

Design of a high-resolution high-stability positioning mechanism for crystal optics

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Introduction

The APS SRI-CAT 3-ID beamline is dedicated to high-energy-resolution x-ray scattering studies in the energy range of 6–30 keV [1]. A special 2.7 cm-period undulator, optimized for peak brilliance, is installed. The beamline's basic components include filters, white-beam slits, integral shutters, and a Kohzu double-crystal monochromator with water-cooled diamond crystals as a premonochromator. The beamline's special components, such as custom-built high-resolution monochromators and a dual-function (collimating or focusing) x-ray mirror system, provide high flexibility for the optical system, so that users can optimize the beamline configuration for various applications. In particular, a four-bounce high-resolution monochromator using a nested channel-cut crystal approach is used to deliver a x-ray beam with meV bandpass for x-ray inelastic scattering experiments [2, 3].

There are design restrictions to the nested channel-cut geometry. Because these two channel-cut crystals are nested within each other, the size of the channel-cut crystals becomes an important design factor. The lack of availability of large crystals with good long-range crystallinity restricts the size of the outer channel-cut crystal. On the other hand, the input beam power absorbed by the first optical surface on the outer channel-cut crystal can reach a fraction of a Joule and can cause crystal local temperature and strain variations. In certain high-energy-resolution applications, these effects become major restrictions to the optical design. To overcome these obstacles, we have developed a novel miniature multi-axis driving structure [4]. The precision and stability of this structure allow us to align or adjust an assembly of crystals to achieve the same performance as does a single channel-cut crystal, so we call it an “artificial channel-cut crystal.” Using this structure, we can make an outer channel-cut crystal large enough to optimize the nested monochromator's performance and compensate the crystal local temperature and strain variations.

Methods and Materials

Design specifications

The artificial channel-cut crystal was designed for a novel nested high-energy-resolution monochromator, which is optimized for an ^{151}Eu nuclear resonance experiment at the energy of 21.542 keV. The high-energy-resolution monochromator uses a symmetric silicon(15 11 3) channel-cut crystal nested within an asymmetrically cut silicon(4 4 0) artificial channel-cut crystal. This optical design can produce a 1 meV-resolution beam with a high throughput [5]. However, if we use a natural channel-cut crystal to make the outer channel-cut crystal, the diffraction

faces can be separated by 200 mm, which makes it difficult to avoid problems associated with strain and temperature variations. We use two asymmetrically cut silicon(4 4 0) crystals, which are each sized 25 mm x 25 mm x 50 mm, to act as an artificial outer channel-cut crystal. The major specification for the artificial channel-cut crystal structure is the angular alignment capability between the two crystals. Due to the 300 nrad Darwin width of the silicon(4 4 0) in this asymmetrically cut geometry, a 50 nrad pitch alignment resolution is needed. Long-term positioning stability is also very important to the artificial channel-cut crystal. In a temperature-controlled environment ($\pm 0.2^\circ\text{C}$), an angular drift rate less than 25 nrad per hour is required. Table 1 lists the design specifications for this (4 4 0) artificial channel-cut crystal [6].

Table 1. Design specifications for a (4 4 0) artificial channel-cut crystal

Max. Overall Dimension	216 mm x 212 mm x 92 mm
Main Shaft Diameter	10 mm
Thickness in Nested Area	30 mm
Single Crystal Size	25 mm x 25 mm x 50 mm
Number of Angular Axes	2
Angular Resolution (Pitch)	50 nrad
Angular Resolution (Roll)	600 nrad
Angular Stability (Pitch)	Drift less than 25 nrad / hour
Angular Stability (Roll)	Drift less than 100 nrad /hour
Angular Range (Pitch)	0.6 degree
Angular Range (Roll)	2 degree

High-stiffness weak-link mechanism design

Designing a miniature multi-axis driving structure with high stiffness and nanometer sensitivity is challenging. The novelty of this new structure is combining the closed-loop controlled piezoelectric transducer (PZT) technology with a novel high-stiffness weak-link design. Using stacked thin metal sheets configured and manufactured by chemical etching and lithography techniques, we were able to design a planar-shaped, high-stiffness, high-stability, weak-link structure for artificial channel-cut crystal use (see Figure 1). 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 whole structure. Two motion structures are designed on the same metal sheet. A wheel-shaped weak-link group acts as a planar rotary shaft, and a parallelogram-shaped weak-link group acts as a linear slide. To optimize the system stiffness, we have chosen overconstrained mechanisms in this design. The precision of the modern photochemical machining process using lithography techniques makes it possible to construct a strain-free (or strain-limited)

overconstrained mechanism on the thin metal sheet. By stacking these thin metal weak-link sheets with align pins, we can construct a solid, complex weak-link structure for a reasonable cost. In our first prototype, 250 μm -thick stainless steel sheets were used. Each group consists of twenty weak-link sheets. A 0.6 degree adjustment range was reached, which agreed with the finite element analysis result.

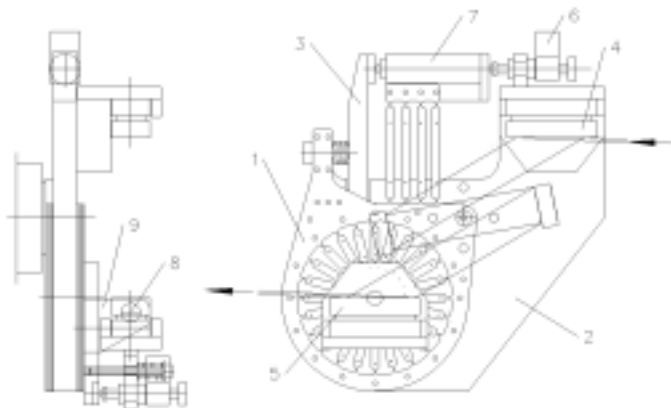


Figure 1: Design of the miniature multi-axis driving structure for an artificial channel-cut crystal. The structure consists of three sub-assemblies: one base structure and two crystal holders. The base structure includes a compact sine-bar driving mechanism for the crystal pitch alignment, which is the key component of the whole structure. There are two groups of stacked thin metal weak-link structures (1) 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 (4 4 0) 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™ [7] (6) with a 20–30 nm step size. A Queensgate™ [8] closed-loop controlled PZT (7) with capacitance sensor provides 1 nm resolution for the pitch fine alignment. A pair of commercial flexure bearings (8) is mounted on one of the crystal holders (9), and a Picomotor™-driven structure (10) provides the roll alignment for the crystal.

Results

Sensitivity test with a laser encoder

We have tested the sensitivity of the weak-link sine-bar structure with a laser Doppler angular encoder. A 200 mm-long aluminum arm is mounted on the center of the planar rotary shaft, perpendicular to the sine-bar. A set of prisms is mounted at the end of the arm as a multi-reflection displacement sensor [9]. During this test, a series of 5 nm incremental steps is applied to the sine-bar by the Queensgate™ PZT. The test result shows a series of angular steps recorded from the laser encoder. The average step size is 33 nrad with a 7 nrad rms deviation.

Stability result from an x-ray experiment

We have tested the first prototype artificial channel-cut crystal as an outer crystal for a four-bounce high-resolution monochromator with nested configuration at the APS 3-ID-

B experiment station. As a typical case, Figure 2 shows a two-hour stability result with a 1 meV bandwidth monochromatic beam. The change in transmitted intensity reflects a combination of the 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. However, we infer that, the contribution of the angular drift of two crystals attached to each other with the mechanism described here is less than 25 nrad per hour.

Discussion

The solution provided here to bring two separate single crystals into a stable alignment at the level of interatomic distances enables new types of x-ray optics designs that go beyond the particular application mentioned earlier. Our motivation to solve a practical problem with respect to the construction of a tunable high-resolution monochromator with an energy bandpass of 1 meV above 20 keV has led to the high-stiffness weak-link mechanism design which is equally applicable to x-ray interferometers, and x-ray wave guides. Therefore, the immediate successful application to an artificial channel-cut crystal assembly for inelastic x-ray scattering studies may be followed by other innovative applications.

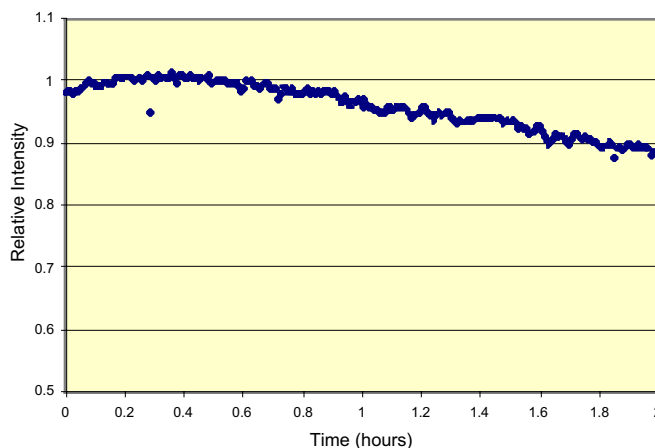


Figure 2: Relative intensity measured by an ionization chamber after the high-resolution monochromator as a function of time. The data are corrected for the decaying current in the storage ring.

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- [8] Queensgate is a trademark of Queensgate Inc., London, England.
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