Mechanical Design of an Ultra-High-Vacuum Compatible Compact Hard X-ray Monochromator with Artificial Channel-Cut Crystal Mechanism

D. Shu, S. Narayanan, and Alec Sandy

Experimental Facilities Division, Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, U.S.A.

Abstract

A compact ultra-high-vacuum (UHV)-compatible x-ray monochromator has been designed and constructed at the Advanced Photon Source (APS) 8-ID beamline for coherent small angle x-ray scattering applications [1]. The monochromator is designed for a small gap between the two crystals (~3 mm) which helps in maintaining a nearly constant spatial offset while changing energy with a single sine-bar mechanism. The sine-bar mechanism is driven by an UHV-compatible linear motion stage with HR-U piezoelectric servomotors from Nanomotion Incorporation. The piezo-electric motors operate under closed loop with encoder feedback to a resolution of 10 nm. An UHV-compatible artificial channel-cut crystal mechanism [2] was integrated in the monochromator to allow that the two independent crystals can be super polished to state-of-the-art for preserving the beam brilliance whereas the same is not feasible with a channel cut crystal. Mechanical designs for the UHV-compatible artificial channel-cut crystal mechanism and the sine-bar mechanism with piezoelectric servomotor drivers are presented in this paper.

OUTLINE

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- *Monochromator Mechanical Design*
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  - *Supporting Structure*
  - *Vacuum Tank*
  - *Sine Bar Structure and Driver*
  - *UHV-Compatible Artificial Channel-Cut Crystal Mechanism*
- *Monochromator Control System*
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INTRODUCTION

Beamline 8-ID-I [1] at the Advanced Photon Source (APS) requires a double-bounce Ge(111) monochromator to produce a coherent beam with the appropriate longitudinal coherence for x-ray photon correlation spectroscopy (XPCS) measurements.

- The monochromator should be mechanically stable so that spurious monochromator motions do not corrupt the fluctuating scattered x-ray signal arising from the sample.
- Moreover, XPCS is a brilliance-limited technique so the monochromator must preserve the beam brilliance by having highly polished diffracting faces.

Unfortunately, the latter has not proven possible with either the current 8-ID-I "traditional" channel-cut design or an enhanced "Z-step" channel-cut crystal [2]; they both produce spatially inhomogeneous (and statistically indistinguishable from each other) monochromatic beams.

INTRODUCTION

Specifically, Fig. 1(a) shows the monochromatic beam produced by our legacy monochromator measured 5-meters downstream of the monochromator via a Roper Scientific™ CoolSnap HQ 1392×1040 pixels area detector and Zeiss™ tube-lens system that yields 0.7 micron-per-pixel resolution. Evidently, the beam incident on the collimating slits that select a coherent fraction of the monochromatic beam is already very non-uniform leading to decreased optical contrast and a decreased XPCS signal-to-noise ratio (SNR) [3].

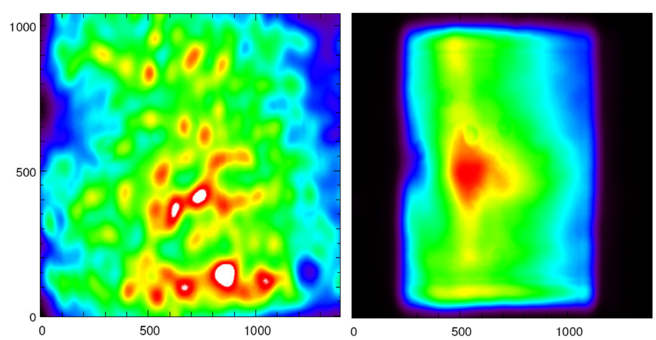
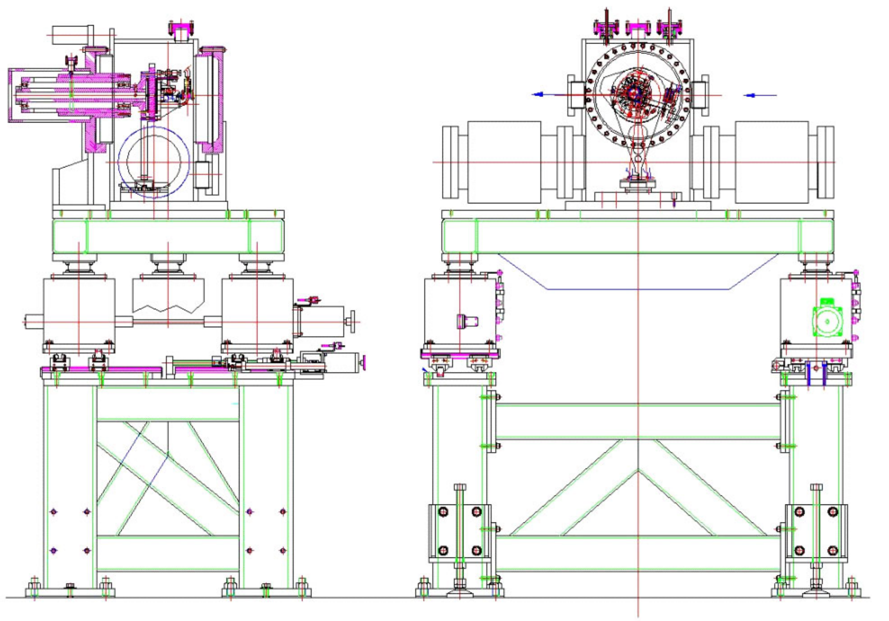


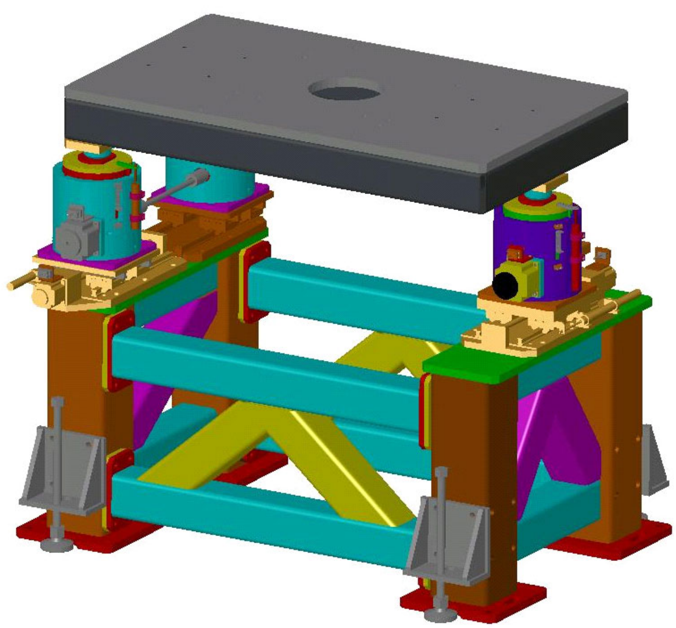
Fig. 5. Old and new Ge(111) monochromatic beams measured with a CoolSnap HQ (0.6 μm/pixel) area detector.

As such, we embarked on a new "artificial" channel-cut monochromator design that facilitates polishing of the diffracting faces while preserving and enhancing the mechanical stability provided by our current monochromator.

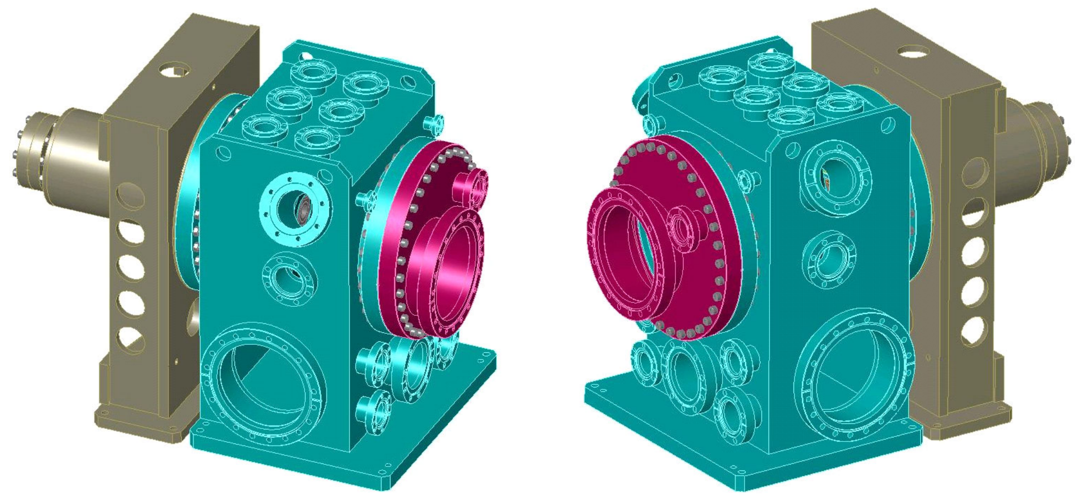
Monochromator General Layout



Monochromator Supporting Structure



Monochromator Vacuum Tank



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Monochromator Vacuum Tank

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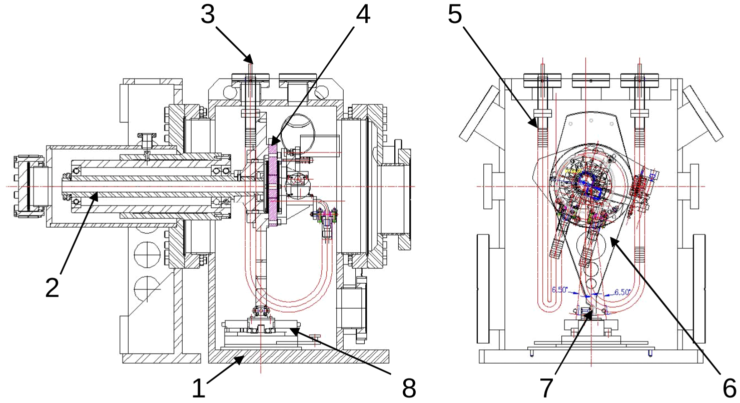
Monochromator Sine Bar Structure and Driver



Detailed cross-sectional side and front views showing the mechanical and vacuum design of the artificial channel cut monochromator. In the center and right panels the "pink" x-ray beam is incident from the right and the monochromatic beam is transmitted to the left.

Referring to this figure, a precision hollow shaft (2) supported by two sets of shaft bearings inside a precisely machined rigid housing permits stable angular rotation of the crystal by means of the sine-bar mechanism. The sine bar (6) is mounted to the shaft (2) with maximized rigidity, permitting the 236-mm-long sine bar to have a 13º rotation range. Using a hardened ruby ball (7) as a precision contact point, the sine-bar arm is driven by a commercial UHV-compatible ceramic-motor-driven linear positioning stage (8) that has 10 nanometer closed-loop linear resolution based on an UHV-compatible linear grating encoder on the stage [5], yielding high angular resolution (42 nrad, theoritically) of the artificial channel-cut assembly. The artificial channel-cut crystal mechanism (4) is attached to front of the sine bar, which is cradled with the high-stiffness precision shaft. The entire assembly, including the channel-cut crystal cage (see below), is contained in a compact UHV vacuum chamber (1) eliminating the use of bellows to transmit the motion and thereby any residual vacuum forces. Water cooling is provided by bellows-insulated cooling lines (3, 5). [8]

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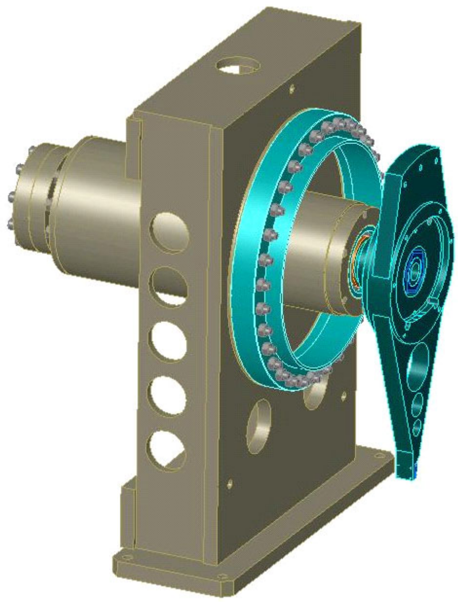
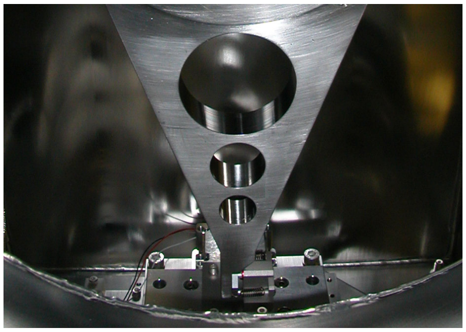
Monochromator Sine Bar Structure and Driver





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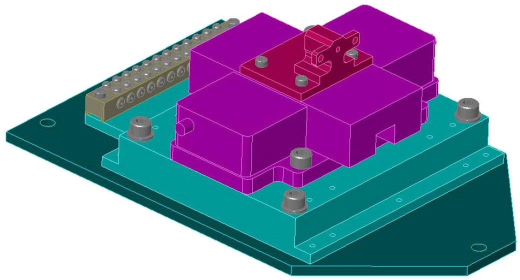
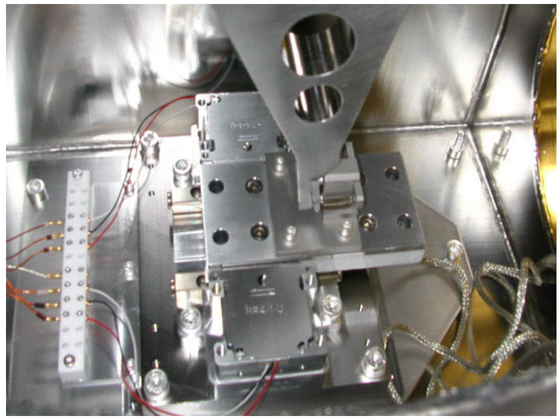
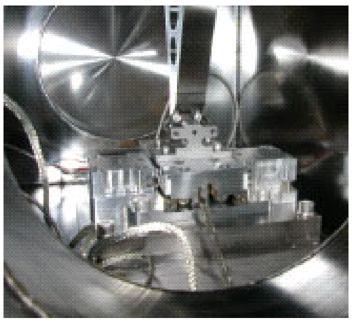
Monochromator Sine Bar Structure and Driver





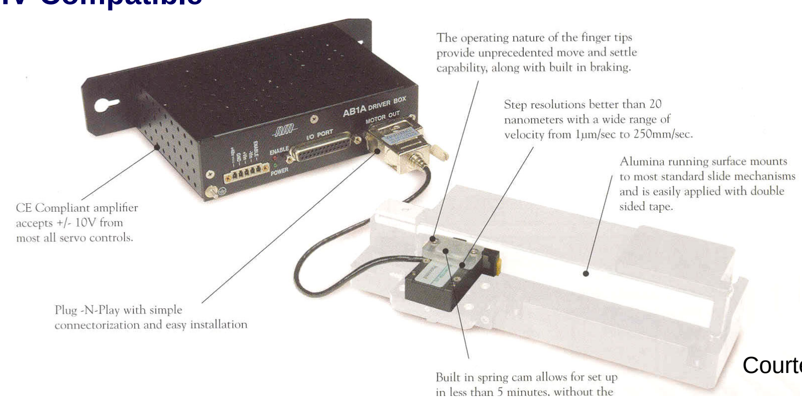


Achieving the mechanical and vacuum design requirements required incorporation of several novel UHV-compatible motion stages. Chief among them is an UHV-compatible linear slide assembly comprised of a precision slide from Alio Industries™, piezoelectric actuators from Nanomotion™, an encoder from Renishaw™, and an ACS Motion™ SPiiPlus stand-alone Ethernet servo controller. The combination delivers exceptionally precise closed-loop positioning in vacuum over extended length scales and velocity ranges. [8]

Monochromator Sine Bar Structure and Driver

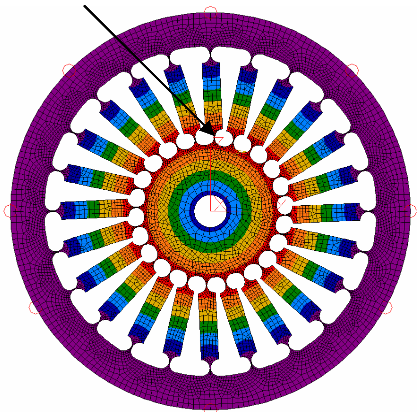
Nanomition™ piezoelectric motor

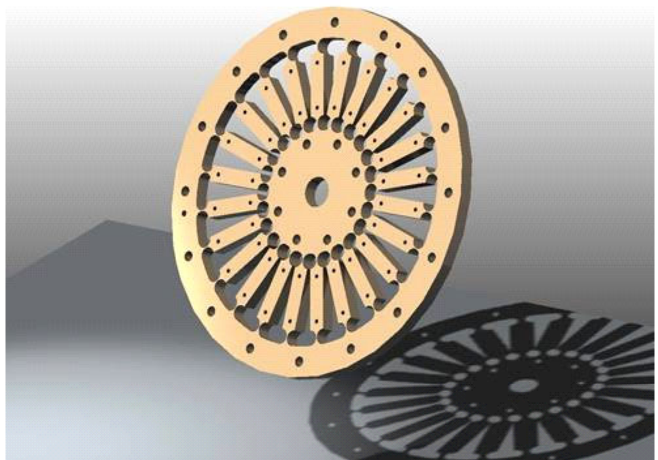
- **Based on the principles of ultrasonic standing waves in piezoelectricity**
- **Operating similarly to DC servo motors with high resolution**
- **Closed-Loop feedback with a grating encoder**
- **UHV-Compatible**



Courtesy of Nanomotion Inc.

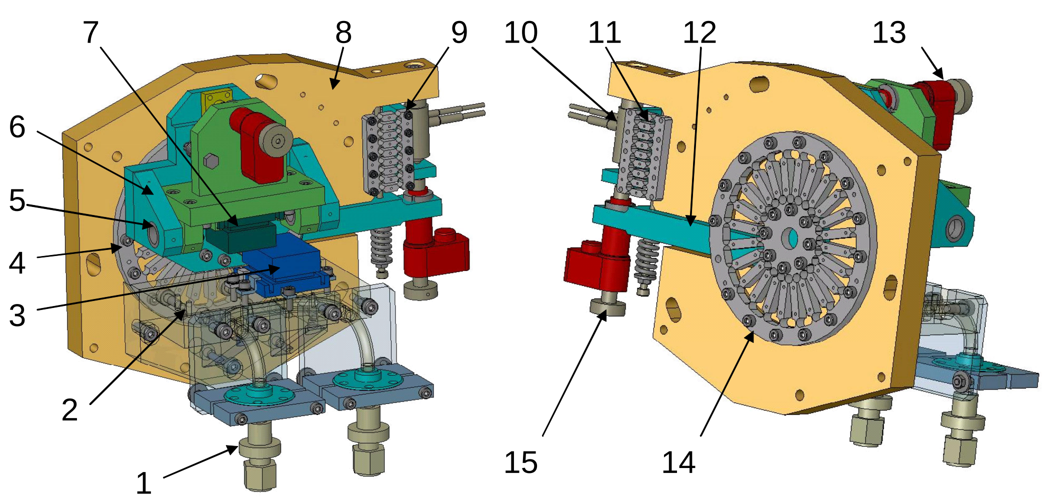
UHV-Compatible Artificial Channel-Cut Crystal Mechanism





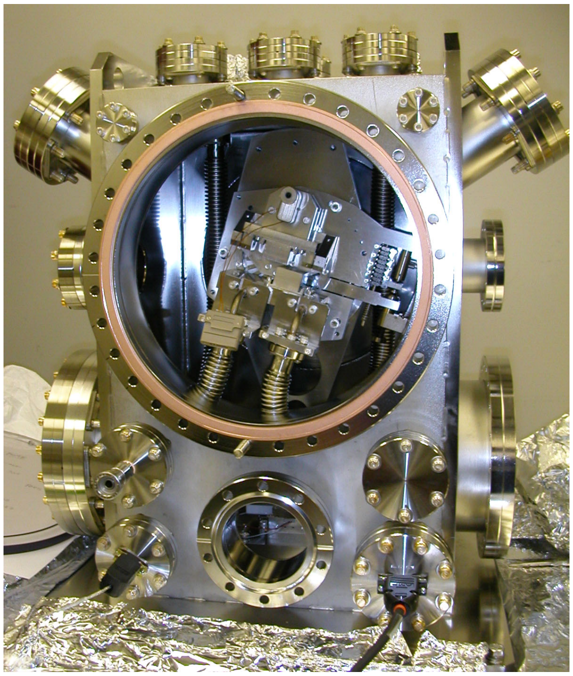
Left: A finite-element simulation for a wheel-shaped rotary weak-link module. It shows the displacement distribution under a 0.89 Nm torsion load on the center part while the outer ring is fixed on the base. Right: A 3-D model of a typical overconstrained rotary weak-link module. It consists of 16 layers of stainless-steel weak-link sheets bonded together with a total thickness of 4 mm.

UHV-Compatible Artificial Channel-Cut Crystal Mechanism

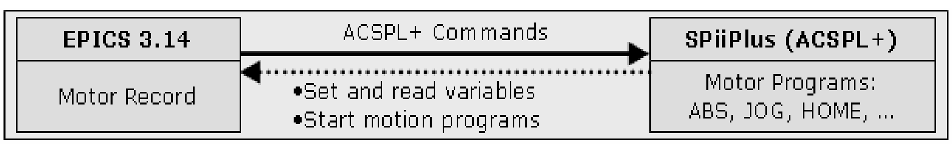


Front side and back side views of a 3-D model for a typical high-stiffness weak-link mechanism for an “artificial channel-cut crystal”. (1) Cooling tube; (2) First crystal holder; (3) First crystal; (4) and (14) Rotary weak-link modules; (5) flexure bearing; (6) Second crystal holder; (7) Second crystal; (8) Base plate; (9) and (11) linear weak-link modules; (10) PZT actuator; (12) Sine bar: (13) and (15) PicomotorTM actuators. [9]

UHV-Compatible Artificial Channel-Cut Crystal Mechanism



Monochromator Control System



- An important control requirement was ensuring that this new monochromator sine bar driver assembly could be seamlessly integrated into Beamline 8-ID's VME-based-EPICS beamline control system.
- This was completed by creation of an EPICS 3.14 device driver so that a standard EPICS motor record can communicate over Ethernet with ASCPL+ command sequences exposed by a socket layer hosted on the ACS Motion™ SPiiPlus motion controller.
- Aside from allowing us to integrate this motion into our control system, the Ethernet-based architecture permits ready access to specialized servo tuning, motion-profile-creation, …, using ACS Motion's™ SPiiPlus MMI Windows™-based application without switching delicate cabling. [8]

Test Results and Discussion

The new monochromator was installed in Beamline 8-ID-I in April 2006. [8]

TABLE 1. APS Beamline 8-ID-I Component Layout

Item	Distance from Radiation Source (m)
APS Undulator A	0.0
Windowless differential pump	25.0
0.3-mm diameter pinhole aperture	27.0
0.15º incident angle horizontal bounce plane Si mirror	29.1
0.1-micron root-mean-square (rms) surface finish Be window	33.0
Artificial channel cut monochromator	65.0
0.1-micron rms surface finish Be window	66.0
Collimating slits (wide open for the measurements presented in Fig. 1)	68.0
Exit flight path 75-micron-thick Kapton™ window	72.0
Roper Scientific CoolSnap HQ detector	72.5

Test Results and Discussion

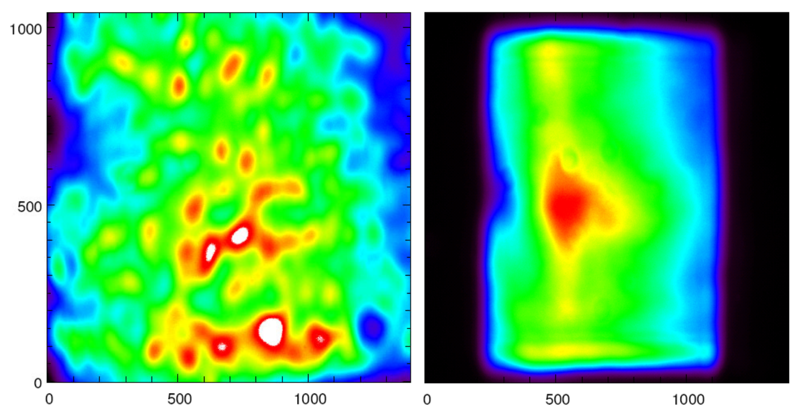


Fig. a Fig. b

Fig. 5. Old and new Ge(111) monochromatic beams measured with a CoolSnap HQ (0.6 μm/pixel) area detector.

Fig. b shows the Ge(111)-monochromatized beam (7.35 keV) produced by the new monochromator. Evidently, its transverse intensity profile is considerably more uniform than that produced by the traditional channel-cut monochromator previously installed in Beamline 8-ID-I (Fig. a). In particular, the variance of the recorded intensities in the center range |X| and |Y| < 67 microns is 50% less in Fig. (b) as compared to that in Fig. a. Moreover, the intensity in Fig. a varies rapidly over considerably smaller length scales versus that in Fig. b with negative implications for the stability of the overall set-up (since the smaller length scale (~ 25 micron) roughly corresponds in size to typical collimating apertures [1]). [8]

Test Results and Discussion

- In conclusion, we have designed and implemented an artificial channel cut monochromator to deliver stable, monochromatic and maximally brilliant x-ray beams to XPCS experiments performed at Beamline 8-ID-I.

- We expect that increased beam uniformity will contribute to enhanced measurement stability and to decreased x-ray-beam brilliance both of which will increase the SNR for XPCS measurements and, consequently, the range of sample dynamics that can be probed.

- Future commissioning activities will probe the effect of the horizontal-bounce mirror (see Table 1) on the intensity variation displayed in Fig. b. [8]

Acknowledgments

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