Designing and commissioning of a prototype double Laue monochromator at CHESS

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Abstract. High-energy X-rays are efficiently focused sagittally by a set of asymmetric Laue (transmission) crystals. We designed, built and commissioned a prototype double Laue monochromator ((111) reflection in Si(100)) optimized for high-energy X-rays (30-60 keV). Here, we report our design of novel prototype sagittal bender and highlight results from recent characterization experiments. The design of the bender combines the tuneable bending control afforded by previous leaf-spring designs with the stability and small size of a four-bar bender. The prototype monochromator focuses a 25 mm-wide white beam incident on the first monochromator crystal to a monochromatized 0.6 mm beam waist in the experimental station. Compared to the flux in the same focal spot with the Bragg crystal (without focusing), the prototype Laue monochromator delivered 85 times more at 30 keV.

1. Introduction

Sagittally-bent Laue monochromators have been in use to focus high-energy X-rays [1]. These monochromators make use of a set of asymmetric Laue crystals to focus the X-rays in the sagittal direction while taking advantage of the anticlastic bending in the meridional direction to minimize or eliminate the effect on the resulting energy resolution due to the vertical opening angle of the synchrotron beam [2].

We designed a prototype monochromator, which consists of sagittal bending devices (benders) for Laue crystals, slits, and translation and rotation stages. The prototype was commissioned on a bending magnet beamline at the Cornell High Energy Synchrotron Source (CHESS). Here, we show the design of the sagittal benders and highlight the results from the commissioning experiments.

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2. Prototype double Laue monochromator

2.1. Prototype sagittal bender

The primary goal of the design of the prototype sagittal bender was to be able to create a symmetric bend with reproducible sagittal bending radius ($R_s$) that will produce a focused beam in the experimental station, given the focal length of the beamline. $R_s$ can be determined by:

$$R_s = \frac{4 \sin \theta_B \sin \chi}{1/F_1 + 1/F_2},$$  

where $\theta_B$ is the Bragg angle and $\chi$ is the asymmetry angle, defined as the angle between the surface normal ad the diffraction plane [2], and $F_1$ and $F_2$ are source-to-monochromator and monochromator-to-experimental station distances, respectively. In addition to controlling the bending radius, twist adjustments in the crystals are necessary to avoid degradation of intensity and energy resolution of the resulting beam.

Two types of benders were considered: a leaf-spring, and a four-bar. A schematic representation of each type is shown in figure 1. In a leaf-spring bender (figure 1(a)), the crystal is clamped at its sides, and each side is mounted on a leaf spring. A sagittal bend is created by applying a force to one leaf spring while the other is fixed. Advantages of a leaf-spring bender are only a single motion is required to create a bend, and the design allows for a good thermal contact for heat exchange. On the other hand, because a force is applied to one side only, the bend is asymmetric – this becomes more problematic at higher energies, where the bending radius becomes smaller (see equation (1)). In a four-bar bender (figure 1(b)), a sagittal bend is created by displacing two inner bars, while the two outer bars remain fixed. With a four-bar bender, a symmetric bend can be created. Moreover, this design allows for a compact size of the bender. However, motions of the two inner bars need to be precisely synchronized, which adds complication to the design.

![Figure 1. Schematics of a leaf-spring bender (a), and a four-bar bender (b)](image)

Evaluating the two options, the four-bar bender was preferred, as compactness and being able to create a symmetric bend were key requirements. In our design, two sets of bending bars are used. Each set of bars is rotated opposite to one another to create a sagittal bend. Each bending bar has rotational freedom to allow the crystal to translate as it bends. A schematic representation of the bending mechanism is shown in figure 2(a). To create a bend, in principle, a moment can be applied to each side of the crystal with two synchronized motors; however, as previously suggested, this is one of the drawbacks of a four-bar bender. To overcome this issue, we implemented a differential screw design consisting of a dual-pitch rod. This rod contains two sections – one portion half the pitch of the second. A schematic representation of the design is shown in figure 2(b). One revolution of the motor shaft can move one point of application of force in the $+x$ direction, while the second point of application of force, mounted to the portion of the rod with twice the pitch moves in the $-2x$ direction, creating equal and opposite displacement.
Figure 2. Schematics of the CHESS prototype four-bar bender showing the bending mechanism (a), and dual-pitch differential screw concept for a symmetric displacement with one motion (b).

Figure 3 shows the final design of the prototype bender. As described previously, a dual-pitch rod is used to actuate a bending motion. One revolution of the motor displaces the large-pitch threaded plate and the motor, each mounted to a translation stage containing a pushrod by the same magnitude in opposite directions. The motion of the pushrods is transferred to rotation in the sagittal cradles, each containing bender bars, through the sagittal extension plates. When the sagittal cradles rotate toward the crystal, the upper bars place compression on the top surface of the crystal, while the lower bars place tension on the bottom surface of the crystal. The bending radius of the crystal can be modified in approximately a 0.25 mm-increment. Rotational axis of each cradle is defined by a pair of sagittal bearings. One of the sagittal bearings is mounted on a twist cradle, which has its axis perpendicular to that of the sagittal cradle – this twist axis is defined by a single bearing.

Figure 3. CAD models of the prototype bender viewed from top and bottom

2.2. Monochromator assembly

Figure 4 shows a model of the prototype Laue monochromator. The monochromator consists of a pair of sagittal benders (D). Each bender is mounted on a two-circle segment tilt stage (C), which in turn, is mounted on a rotation stage (B). The rotation stages provide the pitch motion, while the tilt stages provide the yaw and roll motions. Each rotation stage sits on a vertical (E) and a transverse translation (F) stages. In addition, the downstream assembly travels on a longitudinal translation stage (G), which provides the necessary separation between the upstream and downstream crystals necessary for energy tuning. Not shown in the model is a 5mm-thick aluminum filter, which was used to reduce heat load on the first monochromator crystal.
3. Commissioning experiments
In the commissioning experiments, two 380 µm-thick 100 (h) × 40 (v) mm² Si(100) crystals were used. Each side was parallel to <110>, with the shorter side parallel to the bending axis. The experiments were performed at the B1/2 station at CHESS, which receives 5.9 GeV electron beam from a 0.55 T hard-bend magnet. The horizontal and vertical divergence was 2.5 mrad. The monochromator was located at 10 m from the source. Pitch and bending radius of the monochromator crystals were set to focus 30 keV X-rays (from the Si(111) plane) in the middle of the experimental station, 4 m from the monochromator. The bending radius was 435 mm. Flux of the incoming X-rays was monitored by a 6 cm-long ion N₂-filled chamber, and the beam on a phosphor screen was captured by a digital camera. Figure 5 shows an image of the beam at 4 m from the monochromator. Full-width at half maximum (FWHM) of the focused beam in the horizontal and vertical directions were 0.6 mm and 1.5 mm, respectively. FWHM of the beam on the first monochromator crystal in the horizontal direction was 25 mm. FWHM measurements were made with beam viewing software developed at CHESS. The measured flux in the focused beam was 3.9×10¹¹ ph/s at 200 mA storage ring current, which corresponds to about 85× increases in flux with the Bragg crystals without focusing at the same energy (both measured and calculated); this increase is due to effects from both focusing and anticlastic bending. No degradation of beam quality was observed over several weeks.

4. Summary
We designed and commissioned a prototype double Laue monochromator at CHESS. The monochromator consists of several rotation and translation stage and benders. The design of the benders includes a use of a dual-pitch rod, which allows for synchronized movements of the bender bars with a single motor. The monochromator sagittally focuses a beam that was 25 mm wide at the monochromator, 10 m away from the source to 0.6 mm in the experimental station and 4 m from the monochromator.

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