Highly asymmetric Laue focusing monochromator

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Abstract. By using two highly asymmetric Laue crystals in a dispersive arrangement with a circular profile ($\varnothing$ 8 mm) we have created a sagittally focusing Laue system for the first time. The crystallographic planes (111) of the two Si crystals formed an angle of 7.95° with the entrance surface. The crystals dimensions were 40 mm $\times$ 20 mm and the diffracting surface was a 0.5 mm thick neck between the two circular profiles. The 15.35 keV diffracted beam formed an angle of 0.55° with the exit surface. The calculated focusing distance of the Laue–Laue focusing system was 14 m.

Introduction

Focusing properties of optical systems based on the deviation of the diffracted beam on crystals with an inclined surface were comprehensively studied and published by our group during the past decade. This effect is due to refraction. A broad theoretical as well as experimental study was performed in the past. Most studies focused on the Bragg diffraction case, both symmetric and asymmetric [3,11]. It was shown that this effect may be utilized to sagittally focus the diffracted radiation if the diffraction surface is profiled into a parabolic groove [1,2,5,6,8]. Technical reasons forced us to approximate the parabolic groove into a circular one.

In the case of the Laue based diffractive optics the number of published research papers is much lower [12,13]. To our knowledge no experiment was realized with a highly asymmetrical Laue focusing system. A simple theory presented in [7] which gives the formula for the sagittal deviation δ of the beam diffracted from a sagittally inclined surface in Laue case:

$$\delta = ([r_e \lambda / (2\pi V \cos \theta_B)] [F_{0r} - \rho | F_{hr} | \exp(-M)] \times [\cos \theta_B / \cos(\theta_B + \alpha)] / k) \tan \beta. \quad (1)$$

Here r_e is the classical electron radius, V is the volume of the unit cell, θ_B is the Bragg angle, ρ is the polarization factor, and F_{0r} and F_{hr} are the real parts of the structure factors of the corresponding reflections and $k = 1/\lambda$. The angle α is the deviation of the entrance surface from that in the Laue symmetrical case and β is the inclination angle. From [4], we can calculate a focusing distance f for a parabolic groove.

$$a = (S + f) / (2 N K' f S), \quad (2)$$

$$K' = K(2 + b + 1/b)/(4 \cos \alpha) \quad (3)$$

where S is the crystal–source distance, b is the asymmetry factor, for silicon $K = (1.256 \times 10^{-3}) d_{hkl} [\text{nm}] \lambda [\text{nm}]$, N is the number of diffraction events, α is the deviation of the entrance surface and the symmetric Laue case and a is a parameter from the parabola equation.

First experiment: Laue–Bragg

The first experiment with a highly asymmetric focusing Laue crystal was performed at the ESRF (beamline BM05) and published in [10]. To summarize the experiment: a Laue crystal, Fig. 1, with a flat symmetrical Bragg crystal was used, Fig. 2. The Bragg crystal has two functions, first, to redirect the diffracted beam after the Laue crystal into the FReLoN detector, and second, to suppress the higher harmonics, which would devalue the focusing properties.

Figure 1. Laue crystal with circular groove.

Figure 2. Laue-Bragg arrangement of the first experiment.

The focusing properties of the Laue crystal were proved and measured by taking images of the diffraction at different distances. Focusing distance deduced from the experiment was 43 m. This value does not agree with the calculated one of 360 m. The reason why the measured focus is $8.37 \times$ shorter than the calculated was unknown.

Second experiment: Laue-Laue (focusing)

To improve and enhance the focusing properties and to reduce the sagittal spread created by a Laue-Bragg system, a second experiment at the BM05 with two Laue crystals in a dispersive arrangement was performed, Fig. 3. This arrangement in the Bragg diffraction cancels the sagittal spread [9].

Figure 3. Laue-Laue arrangement of the 2nd experiment.

Figure 4. Observed interference fringes.

The goal was to apply this property also in the Laue diffraction for which the cancellation should theoretically work. To the authors' knowledge, no experimental proof of this assumption was made. By searching for the diffraction after the first and the second crystal separately, scattering effects and interference fringes were observed, Fig. 4. After the two crystals were set into the diffraction position and aligned into a line a weak diffraction was observed, Fig. 5 – red ellipse. The angular range of the diffraction was 14.4 arcsec. Using the intensity distribution of the diffraction a calculated FWHM of 3 arcsec was obtained. The simulated FWHM (XOP 2.3) of our Laue diffraction was 4 arcsec. This serves as a proof of the detection of a Laue diffraction after two crystals. The set-up of the FReLoN camera was so immobile that a movement downstream was not possible and therefore a series of images with a shrinking focus were not taken. The diffracted spot was 1 mm wide (after 0.35 m), with an impinging beam of 5 mm this gives a focusing distance of 1.75 m. The measured focusing distance is $8 \times$ shorter than the calculated one.

Third experiment: Laue–Laue (harmonics separation)

To explain the focal spots, the interference fringes and to observe a clear focusing effect a third experiment at BM05 was performed as in Fig. 3. The interference fringes were located above the diffraction, i.e. on a side where they according to the dynamical theory should not be. This was a sign that a surface effect due to the high roughness and small incident angle (0.55°) was observed. Therefore the internal walls of both crystals were again polished to smooth away the small bumps (sinusoidal surface shape) left after the drilling process. After the second polishing, no interference fringes were observed. The focal spots were now more clearly visible – due to better surface quality, Fig. 6a-b.

Figure 5. Diffraction after two Laue crystals.

Figure 6. Observed “coma”.

The scatterings were observed in two planes. They were very similar to something well known to visible optics – the coma. The critical angle for Si at 15.35 keV is $\Theta_c = 0.12^\circ$. By rocking the crystal from the horizontal position to the diffraction angle, 0.55° , the crystals tilt passes the angle of total reflection and creates something like a coma, Fig. 6a. By rocking the second crystal into the opposite direction, the focal spot appears on the other side, Fig. 6b. To capture a series of images verifying the focusing properties a laterally mobile detector instead of the FReLoN was used. Because of the low sensitivity of the detector and the flux consuming experimental set-up (two Si crystals in transmission and several meters of air path) no diffraction was detected. Detailed analysis of the images showed a double smile in the diffraction after one crystal, Fig. 7. By slowly rocking with the first crystal, first one smile appeared (smaller, stronger) and afterwards a second smile appeared (larger, weaker). This was a clear indication of higher harmonics contamination. In fig. 8 is plotted the Darwin-Prins curve of a symmetric Si(111) Bragg diffraction for 15.35 keV and the Si(333) for 46.05 keV for the beamline monochromator of BM05. The higher harmonic energy is partially overlapping the fundamental energy, therefore the two smiles represent two different energies.

Figure 7. Higher harmonics separation by refraction.

Figure 8. Darwin–Prins curves of Si(111) for 15.35 keV and Si(333) for 46.05 keV.

If one compares the X-ray images after 1.19 m and 7 m after one crystal, a clear separation with a growing distance of the two smiles is visible, Fig. 9. The smiles are also getting narrower which proofs the focusing properties. The extracted focusing distance based on the shrinking smiles is 38.7 m. If one compares this to the first experiment (43 m), one gets a good agreement. This clear separation of higher harmonics gives a good possibility for a new kind of separation method or instrumentation based on diffractive–refractive optics.

Figure 9. Harmonics separation and focusing due to refraction.

Conclusions

The first experiment with a Laue–Bragg crystal system proved the focusing ability of a profiled grooved crystal in the Laue geometry. The imperfection of the sagittal focusing of the Laue–Bragg system manifested itself into the vertical spread of the focused smile. To overcome this, a second experiment with a Laue–Laue crystal system was performed. The verification of focusing properties of a Laue–Laue crystal system was partially demonstrated. A direct proof based on a series of images in different distances from the crystals was impossible due to a low intensity of the diffracted spot. The focusing distances of separated crystals were verified and repeated in two following experiments. All observed focal spots and interference effects were explained. The difference factor of 8 between the measured and calculated focusing distance points to a systematic mistake in the used theory, which will be investigated in the future. Furthermore clear harmonics separation due to a different strength of the diffractive–refractive effect for different energies was observed. This could lead to an interesting harmonics separation method or instrumentation.

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