

Fast X-ray shutter based on double-crystal adaptive X-ray optics monochromator

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Received 12 September 2025 ♦ Accepted 31 October 2025 ♦ Published 30 December 2025

Citation: Protsenko AI, Korzhov VA, Petrov II, Eliovich YaA, Kubasov IV (2025) Fast X-ray shutter based on double-crystal adaptive X-ray optics monochromator. *Modern Electronic Materials* 11(4): 237–242. <https://doi.org/10.3897/j.moem.11.4.171888>

Abstract

Within the framework of a fast double-crystal synchrotron monochromator based on adaptive X-ray optics elements – ABXO (Adaptive Bending X-ray Optics) prototype developing, the possibility of its use as a fast X-ray shutter was demonstrated.

This work proposes two operational modes for the shutter, which differ in the generated X-ray pulses parameters and depend on the ABXOs operating mode. Achievable temporal parameters of the generated X-ray pulses were estimated and the prospects for their application in time-resolved X-ray research methods are considered.

Keywords

adaptive X-ray optics, X-ray shutter

1. Introduction

Specialized fast double-crystal X-ray monochromators are widely used at synchrotron sources [1, 2] to implement various methods, primarily the quick-scanning X-ray absorption spectroscopy (QuickXAS) method with a time resolution on the order of 10^{-2} to 1 s per spectrum. Such time resolution is necessary for *in situ* studies of various dynamic processes in chemistry, physics, and biology occurring in the corresponding time scale of 1 to 10^3 s. The most demanded studies are of catalytic reactions [3], electrochemical processes in fuel cells [4], and biological processes [5].

The designs of existing fast monochromators are based on the design of classical double-crystal monochromators, where each diffraction element is positioned using a set of precise goniometric positioners. However, fast

monochromators use additional translators for diffraction elements positioning, allowing its faster and more frequent movement, for example, by using fast piezoelectric translators or special direct-drive motors. This significantly speeds up the process of adjusting the monochromatic beam parameters and opens up new possibilities for implementing time-resolved research, including QuickXAS methods.

In paper [6] was presented a uniquely designed double-crystal monochromator prototype with adaptive bending X-ray optics elements (ABXO), which are based on bidomain LiNbO_3 single crystals. One end is cantilever-mounted in a special holder on the monochromator's goniometric positioners, while a thin Si crystal, acting as the diffraction element, is attached to the loose end. The main advantages of the bidomain LiNbO_3 crystals and the reason it was chosen over widely used PZT

piezoceramic actuators are absence of hysteresis in bi-domain LiNbO_3 crystals [7] and high predictability of their properties [8], as it eliminates the need for additional feedback systems to control the angular position of the element.

This type of ABXO has been successfully used previously for fast control of spatial [9–11] and spectral [12, 13] monochromatic beam parameters in a single-crystal monochromatization scheme. Further work in this direction led to the creation of a double-crystal monochromator prototype based on two independent ABXOs. With full synchronization of the two ABXOs and their angular position match at every moment of time, a monochromatic beam continuous generation with rapidly modulated energy in the range of 300–500 eV occurs, which is the intended operating mode of the ABXO double-crystal monochromator.

However, during asynchronous movement, beam generation does not occur continuously, but only when the angular positions of the two ABXOs coincide. Thus, the possible ABXO double-crystal monochromator usage as an X-ray shutter (pulse generator) was considered. This paper provides an estimate of the main pulse parameters (duration and repetition rate) achievable using the ABXO double-crystal monochromator in the X-ray shutter mode.

2. X-ray pulse generation, harmonic mode

Figure 1 shows a cross-section view of the ABXO double-crystal monochromator. Its principle of operation is similar to classical double-crystal monochromators: the device is placed on the axis of the X-ray beam; using a system of mechanical positioners, the ABXOs are arranged in a double-crystal, symmetric diffraction scheme $(+n, -n)$ for the selected energy of the monochromatic beam. Then, by applying a control signal to the bending actuators, angular deflection up to 1 deg for the ABXO diffraction elements is induced.

Since the ABXOs are controlled and moved independently, the condition for double diffraction, necessary for generating monochromatic radiation, is fulfilled when the angular positions of the ABXOs coincide within the Darwin width (Darwin curve) of the used diffraction crystals. In the synchronous operating mode, the ABXOs angular deflection coincides at every moment of time, resulting in continuous generation of monochromatic X-ray beam after double diffraction on ABXOs. In the synchronous mode, a harmonic control signal with a frequency matching the natural resonant frequency of the ABXO is used, allowing for predictable ABXO angular position

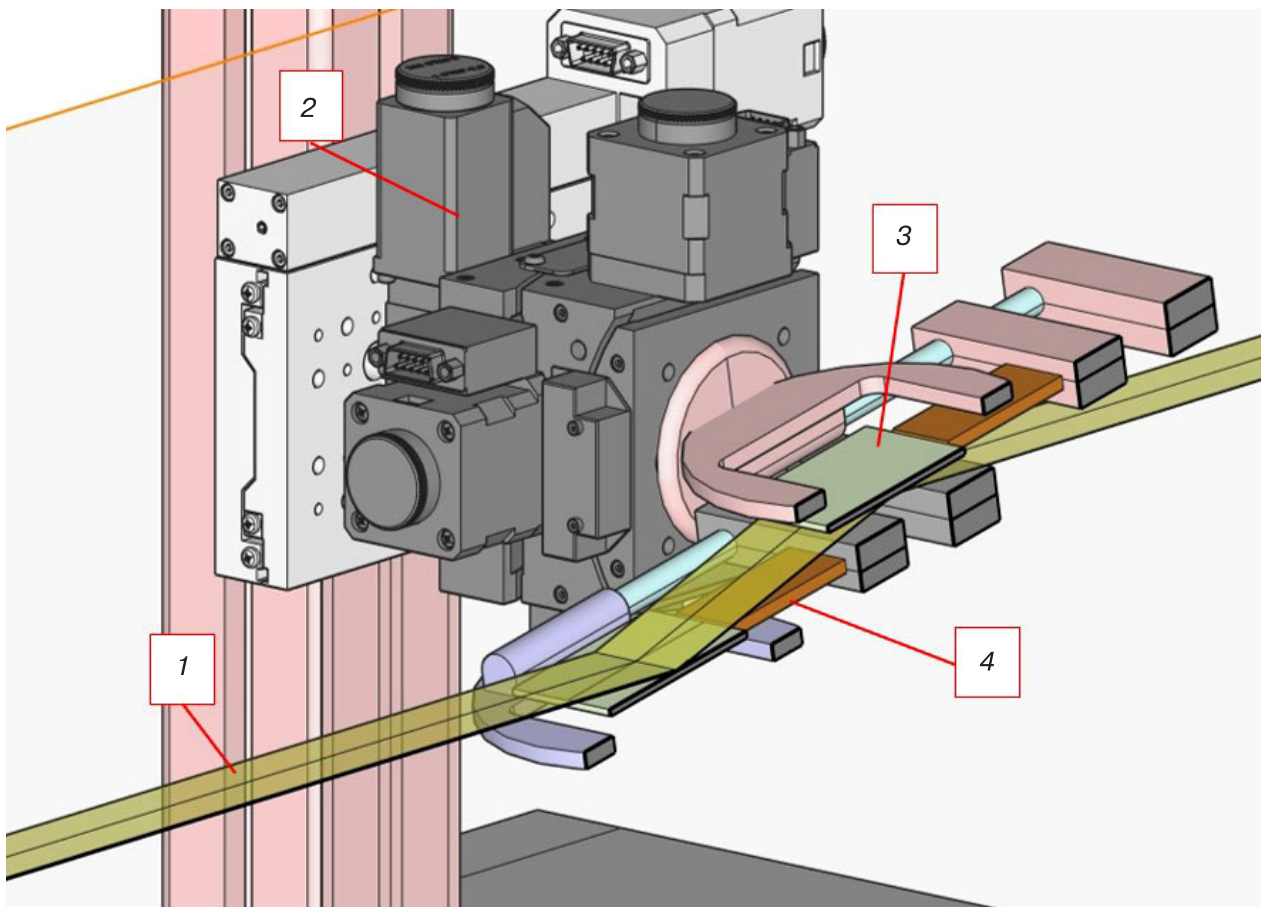


Figure 1. ABXO double-crystal monochromator cross-section view: (1) X-ray beam path, (2) ABXO goniometer system, (3) ABXO #1, (4) ABXO #2

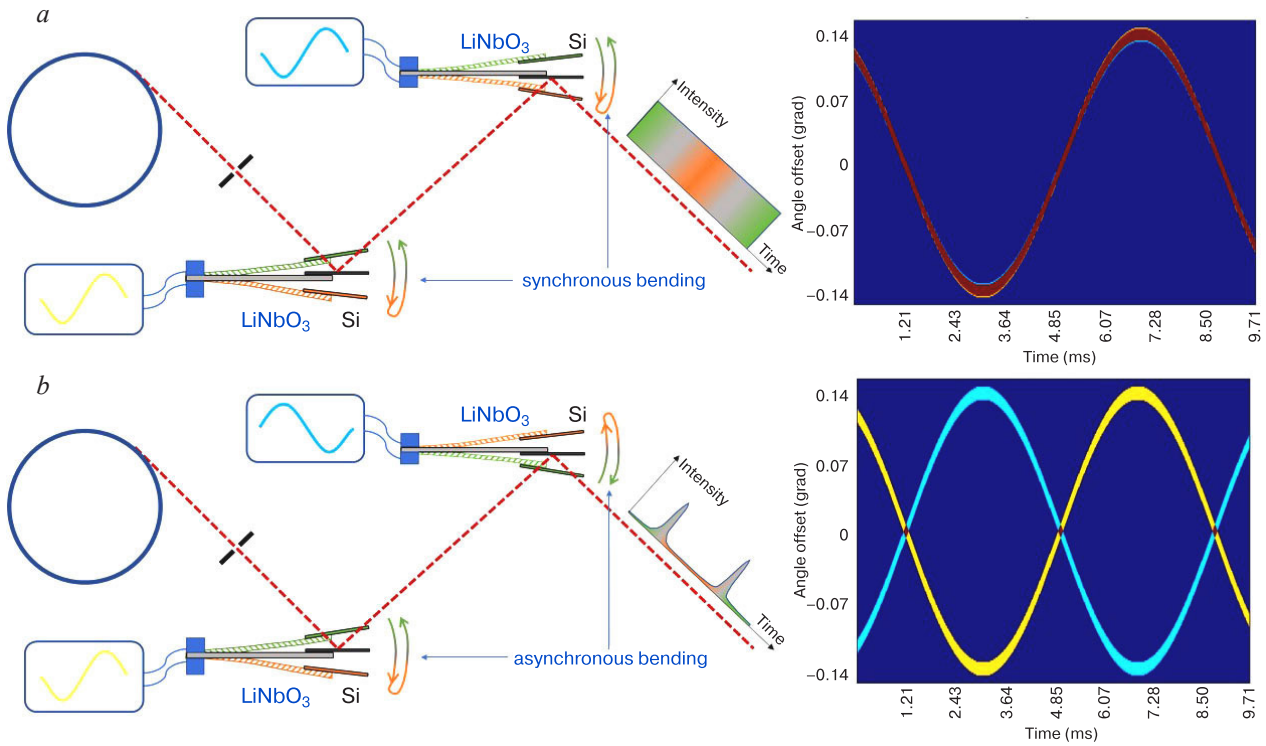


Figure 2. ABXO synchronization schemes and diffraction elements angular position dynamics with harmonic control signal in (a) synchronous and (b) asynchronous mode

with the maximum achievable angular range. The time dependencies of the angular deflection of the ABXO in harmonic mode are described by the formulas:

$$\theta_1(t) = \theta_0 + \Delta\theta_1 (\sin \omega_1 t + \varphi_1);$$

$$\theta_2(t) = \theta_0 + \Delta\theta_2 (\sin \omega_2 t + \varphi_2), \quad (1)$$

where $\theta_{1,2}(t)$ is the angular position of each ABXO at time t ; θ_0 is the initial angular position of the ABXO, set by the goniometric positioners; $\Delta\theta_{1,2}$ is the maximum angular deviation of the ABXO; $\omega_{1,2}$ is the oscillation frequency of the ABXO; $\varphi_{1,2}$ is the oscillation phase of the ABXO.

The principle of generating a monochromatic synchrotron beam using two ABXOs is shown in Fig. 2. The ABXO relative positions are determined by the control signals, setting synchronous and asynchronous operating modes. Time intervals of ABXOs' angular positions coincidence and the monochromatic beam generation are marked in red.

In the full synchronization mode, the frequency and angular range of oscillation coincide, and the phase of the control signal is finely adjusted taking into account the signal delay from the generator to the ABXOs. ABXOs angular position coincidence occurs at any moment in time, generating a continuous beam (Fig. 2a).

$$\Delta\theta_1 = \Delta\theta_2;$$

$$\omega_1 = \omega_2;$$

$$\varphi_1 = \varphi_2 + \Delta\varphi. \quad (2)$$

To generate an X-ray pulse with minimum time duration with a harmonic control signals, the ABXOs must move asynchronously, with a phase shift of π . ABXOs angular positions coincidence occurs in the center of the angular tuning range, where their relative speed is highest (Fig 2b).

$$\Delta\theta_1 = \Delta\theta_2;$$

$$\omega_1 = \omega_2;$$

$$\varphi_1 = \varphi_2 + \Delta\varphi + \pi. \quad (3)$$

The ease of implementing the asynchronous harmonic mode lies in the fact that one can first achieve synchronization of the ABXOs and then shift the control signal of one of the ABXOs by π .

Testing of the ABXO double-crystal monochromator prototype in the X-ray shutter mode was carried out at the PRO beamline of the “KISI-Kurchatov” synchrotron radiation source.

3. Results analysis, harmonic mode

The controlling harmonic signals for the ABXOs were set to asynchronous mode with an oscillation frequency of 100 Hz. A series of measurements were performed for different amplitudes of the control signal, which affects the range of ABXOs angular oscillation and their speed of movement at the moment of angular position coincidence, and consequently, the duration of the generated X-ray pulse. The duration and shape of the pulse were recorded using the time sweep of the detector signal by a multichannel analyser (MCA). The results are shown in Fig. 3 and Table 1.

As the voltage of the harmonic control signal increases, the duration of the generated X-ray pulses decreases. At a voltage of 30 V, which is the operational voltage for the ABXO in continuous mode, the pulse duration is 9.1 μs , which is comparable to existing mechanical X-ray shutters based on rotating slotted devices used at synchrotron beamlines [14, 15]. The non-gaussian pulse shape is associated with the asymmetric diffraction reflection curve of the X-ray diffraction element used for preliminary setup of the entire monochromator.

The advantage of the harmonic control signal is the minimal achievable time of the generated pulses; however, the pulse repetition rate in harmonic mode is determined by the ABXO oscillation frequency. The ABXO oscillation frequency, in turn, must be close to the natural resonant frequency of the bending actuator (10^3 Hz) to achieve a high value of the angular tuning range. Thus, to enable flexible adjustment of the pulse repetition rate or pulse activation on command, using a trapezoidal form of control signals was proposed.

4. X-ray pulse generation, trapezoidal signal

The principle of using a trapezoidal control signal for generating X-ray pulses with the double-crystal generator based on ABXO is shown in Fig. 4. Similar to the harmonic signal, the pulse is generated at the moment the ABXOs angular positions coincidence during their counter movement at the moment of the signal's rising and falling edges. The pulse time duration will depend on the ABXOs movement speed, i.e., on the rise/fall time of the trapezoidal signal, but this parameter is limited during pulse generation.

The reason is that when a trapezoidal control signal is applied, the ABXO, which has its own oscillatory characteristics, does not move strictly in accordance with the control voltage [16]. Parasitic oscillations occur, the amplitude of which depends on the signal's slew rate (rise/fall time). When the amplitude of the parasitic oscillations exceeds half the amplitude of the trapezoidal

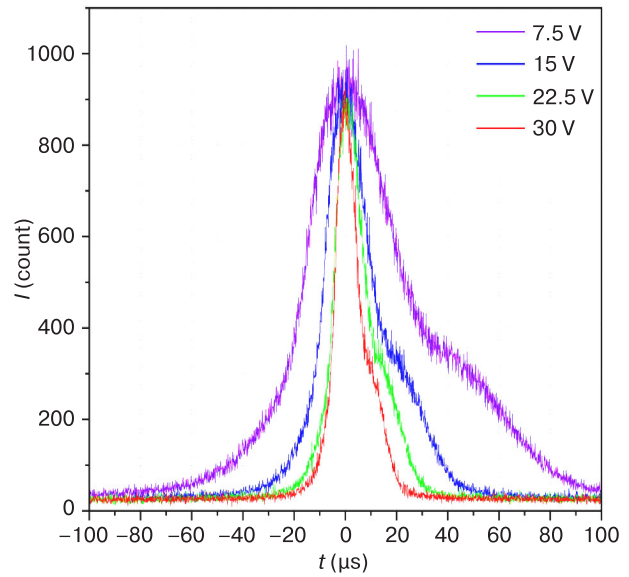


Figure 3. X-ray pulses generated at different amplitudes with the harmonic control signal

Table 1. Angular oscillation range and generated pulse duration for different values of harmonic control signal amplitude

Control signal voltage (V)	Angular oscillation range (arc sec)	X-ray pulse time (μs)
7.5	572	34.9
15	1218	18.2
22.5	1917	12.1
30	2655	9.1

signal (see Fig. 4), additional moments of the ABXOs' angular positions coincidence occur, resulting in extra unnecessary generated X-ray pulses.

A second series of experiments was conducted on the equipment used for pulse generation with the harmonic control signal. A trapezoidal control signal was used with a signal amplitude of 45 V and a frequency of 1 Hz. The limit for the signal's slew rate (rise/fall time) at which no additional pulses are generated was determined

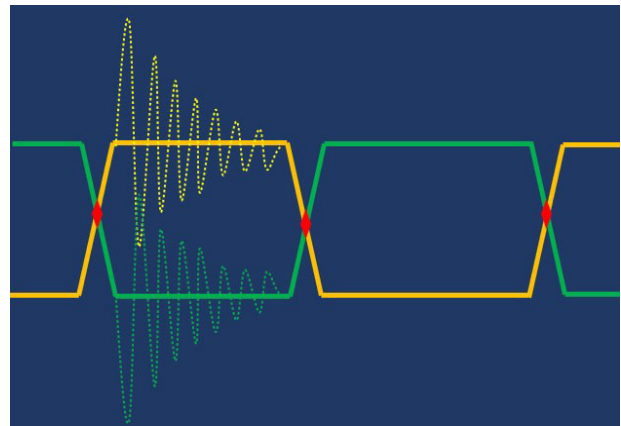


Figure 4. ABXOs angular position dynamics with trapezoidal control signal and ABXOs parasitic oscillations

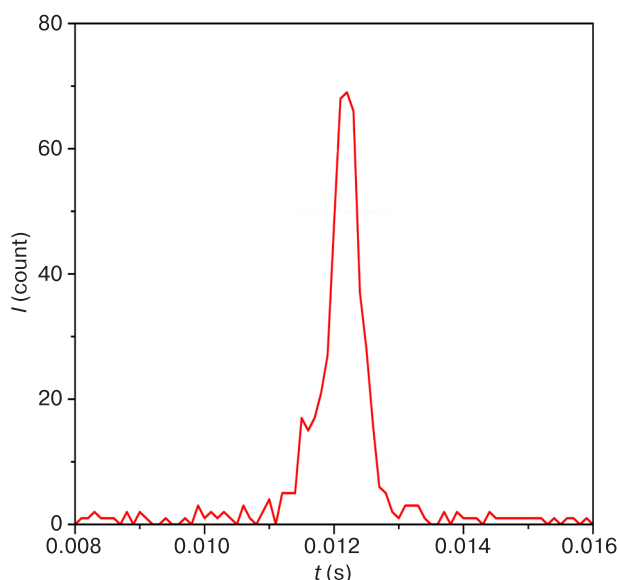


Figure 5. Generated X-ray pulse with a trapezoidal control signal

experimentally: 100 ms. The pulse obtained in this mode is shown in Fig. 5; the pulse time duration is 482 ms.

5. Analysis of results, trapezoidal mode

Considering the technical limitations due to the ABXO parasitic oscillations when applying a control signal different from the harmonic form, the minimum achievable pulse time with a trapezoidal control signal was 482 ms, which is several orders of magnitude larger than when using a harmonic control signal. Also, some instability in the peak generation timing was noted. Presumably, this is related to the aforementioned parasitic oscillations of the ABXO, which lead to deviations in the angular positions of the ABXO at the start of the signal's rising/falling phase, resulting in the coincidence of the angular positions of the ABXOs also occurring with deviations.

However, the trapezoidal control signal allows for generated X-ray pulses repetition rate fine adjustment, which

may be more important than short pulse time and high temporal stability, if X-ray pulse repetition rate 100 Hz in harmonic mode is too high for experimental setup.

Conclusions

The paper presents a method for generating X-ray pulses using a double-crystal monochromator based on adaptive X-ray optics elements. Given that the primary purpose of this monochromator is to conduct time-resolved X-ray studies through fast spectral characteristics modulation of monochromatic X-ray, using the monochromator in the fast X-ray shutter mode will expand the device's capabilities and allow its use for implementing time-resolved experiments in the pump-probe methods with time resolution up to 9 μ s.

It also should be noted: unlike the conventional slotted X-ray choppers which modulate the temporal structure of the beam but do not change its spectral characteristics, using the ABXO double-crystal monochromator results in monochromatic beam generation, which can be both an advantage and a disadvantage depending on the experimental tasks.

Acknowledgement

The work was carried out within the state assignment of NRC "Kurchatov Institute". The bidomain crystals for ABXOs were produced with financial support from the Russian Science Foundation (grant No. 24-19-00876, <https://rscf.ru/en/project/24-19-00876/>).

Author contributions

Developed experimental method and carried out experiments – A.I. Protsenko; assembled experimental setup and carried out experiments – V.A. Korzhov; processed experimental data – I.I. Petrov; general leadership – Ya.A. Eliovich; provided ABXO for experimental setup – I.V. Kubasov

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