High repetition rate X-ray chopper for time-resolved measurements

Pump-probe time-resolved measurement using pulses of synchrotron radiation is a measurement technique that can achieve time resolution similar to the single-pulse width of synchrotron radiation. In order to perform pump-probe time-resolved measurements, it is necessary to select individual X-ray pulses, because the frequency of (probe) pulses is usually much higher than that of the stimulation to the sample (pump). As a means of selecting single X-ray pulses, X-ray choppers have been adopted at many synchrotron radiation facilities. They have the advantage that time resolution is not necessary for the detector in experiments using X-ray choppers, however, the repetition frequency of the X-ray single pulse obtained using the X-ray chopper installed in SPring-8 was limited to several kHz [1]. This is comparable to the repetition rates of typical regenerative amplifier femtosecond pulse lasers, and X-ray choppers have successfully been used for pump-probe experiments with femtosecond pulsed lasers. On the other hand, studies of electronic devices, e.g. next generation memory, that allow electrical stimulation at rates of 100 kHz have been proposed, and furthermore, femtosecond amplifier pulsed lasers with repetition frequencies of the order of 100 kHz have been realized in recent years, so X-rays choppers which can reach these repetition rates are required. In order to meet this demand, we have developed such a high repetition rate X-ray chopper.

High repetition rate X-ray choppers can be realized using X-ray diffraction [2], however this changes direction and position of the chopped X-rays. By contrast, blocking the X-rays except at specific times does not affect these properties and is the approach used here. Figure 1 shows three types of X-ray choppers [3-5]. Type A is similar to standard optical choppers, with a rotating slotted disc. The motor-axis is parallel to the X-ray beam and this type is referred to as "parallel." In contrast, the triangular chopper B rotates about an axis perpendicular to the beam, and is referred to as the "perpendicular type." For both A and B, each slit transmits one X-ray pulse each revolution. The perpendicular type blocks the X-rays at both the entrance and the exit, so for the same rotational speed and radius offers half the temporal width of the parallel type.

The chopping method which we adopted for our high repetition rate X-ray choppers described here is of type C. Similarly to type B, the axis of rotation is perpendicular to the beam, offering the advantage of short opening time. The chopper shape is a disc, similar to type A, but rather than using slits, the X-rays pass through grooves cut along radial lines on the surface of the disc. Since the X-rays pass through the center of the disc, this design offers twice the chopping speed of types A and B for the same rotating speed. Furthermore, the grooved design is of low fabrication cost, and is well suited to high chopping frequency applications, which require a large number of grooves.

Figure 2(a) shows a photograph of the chopper apparatus. The upper part is the chopper disk housing, which operates in vacuum to reduce friction, and the lower part contains the motor, which is an air-spindle design (ShinMaywa Industries, Ltd. SPM30). The speed and phase of the motor can be controlled by a phase-locked loop linking the SPring-8 RF pulse to the eight pulses per revolution required to control the motor. Figure 2(b) shows a photograph of the chopper disc. The X-rays pass along the direction shown through grooves in the 140-mm-diameter disc. To allow high rotation speeds the disc must be light, so that suitable materials are aluminum and titanium. To allow use at X-ray energies of up to 40 keV, titanium was chosen. As shown in Fig. 2(c), alternate grooves have different widths and depths, making up 54 pairs at regular intervals. The grooves labelled 'A' are 250 μm wide and 500 μm deep. Grooves B are 250 μm wide to a depth of 1 mm, with a further 110-μm-wide deep groove to a depth of 1.5 mm. When the disc rotates at 29,000 rpm and is

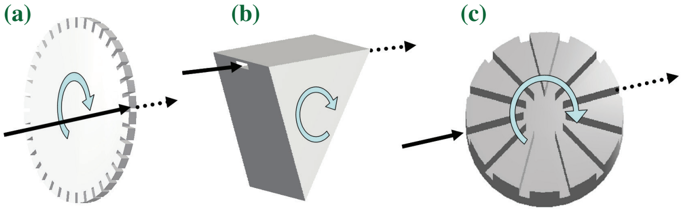

Fig. 1. Three types of X-ray chopping methods.

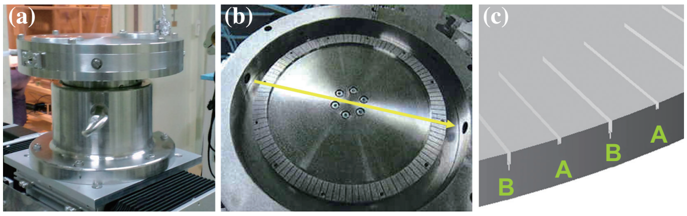

Fig. 2. Photograph of **(a)** the X-ray chopper apparatus and **(b)** the X-ray chopper disc. **(c)** Computer graphic diagram of the groove structure on the disc (b). The yellow arrow in (b) shows the X-ray pass.

synchronized to the SPring-8 RF signal, the 250-μm-wide grooves offer an opening time of 1.17 μs, and the 110- μm-wide grooves an opening time of 0.52 μs, respectively. These allow selection of single bunches in the '1 bunch + 11/19 filling', '5 bunch + 1/7 filling' and '12 bunch + 1/14 filling' modes. The different depths provide two different chopping frequencies. Using depths of up to 500 μm, both A and B grooves transmit the beam, giving a chopping frequency of 52.2 kHz, which corresponds to once every four full passes of the SPring-8 bunch structure. Using depths greater than 500 μm, only groove B transmits X-rays, giving a chopping frequency of 26.1 kHz (once every eight full passes of the bunch structure).

Figure 3 shows results from operating the chopper during the '5 bunch + 1/7 filling' mode. The test was carried out at **BL13XU**, using a 12.4 keV X-ray beam. X-rays transmitted by the chopper hit a copper plate, and scattered X-rays and fluorescence were detected using an avalanche photodiode. A time spectrum was collected by the mulch channel scaler. Figure 3(a) shows the time structure of X-ray pulses without using the chopper. The bunch structure consists of 5 isolated bunches, and a multi-bunch portion, which increases the total stored current to 100 mA. Figure 3(b) shows the results when using the chopper to select one single bunch X-rays every four periods. It is clear that all other pulses are effectively blocked by the chopper. Figure 3(c) shows the results of using only grooves B (Fig. 2(c)), resulting in the transmission of one single bunch X-rays every eight periods. The ratio of the selected pulses to the suppressed pulses is around 1:5,000,000, sufficient for many time-resolved measurement techniques.

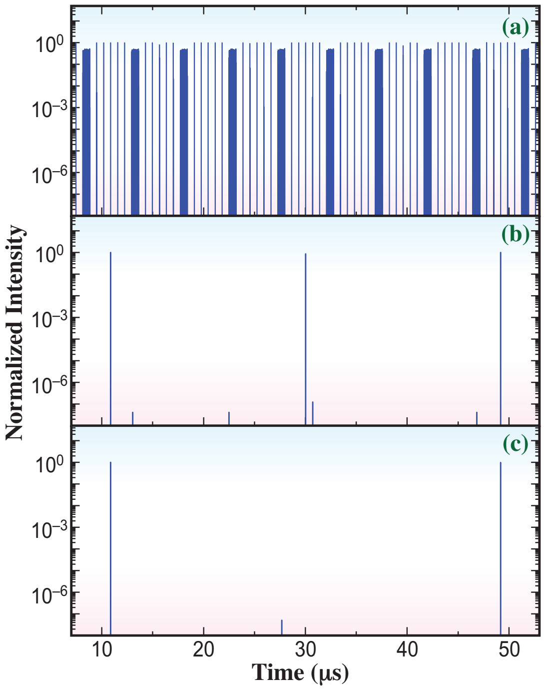

Fig. 3. Time structure of X-ray pulses of **(a)** before chopping, **(b)** chopping with grooves A and B, and **(c)** chopping with groove B.

In summary, we have developed an X-ray beam chopper suitable for pump-probe studies of electronic devices and using high-frequency pulsed lasers it can select a single pulse every four or eight periods of the SPring-8 bunch structure. Time-resolved measurements with the high repetition rate chopper enable the use of bending-magnet beamlines. As well as the chopper described here, we have also developed an aluminum chopper suitable for X-ray energies less than 20 keV, and also a smaller, lower cost version. We anticipate that their use will facilitate many time-resolved studies.

Hitoshi Osawa*, Togo Kudo and Shigeru Kimura

SPring-8/JASRI

*E-mail: hitoshio@spring8.or.jp

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