A fast X-ray chopper for single-bunch extraction at synchrotron sources

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A new X-ray chopper system based on air-bearing technology was developed in a joint project between the Paul Scherrer Institut and DESY. The X-ray chopper wheel of 150 mm diameter has a slit width of 50 μm , which corresponds to an opening time of 230 ns at 30 000 r min^{-1} . The wheel is equipped with either one or two slits at slightly different radii, resulting in repetition frequencies of 500 and 1000 Hz. To reduce air friction the wheel is operated in a reduced-pressure environment. The chopper is controlled by a specially developed phase lock loop controller, which is synchronized to the master bunch clock of the synchrotron. The very small and constant friction of the bearing and the high mechanical accuracy of all mechanical components in combination with the high-precision controller resulted in a very small long-term jitter of less than 3 ns. The chopper is capable of isolating X-rays generated from a single bunch of the future PETRA III storage ring at DESY operated in 40-bunch mode.

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1. Introduction

The static molecular structures of a vast number of small molecules and an increasing number of biological macromolecules are known. Their physical properties can be determined with quantum chemical calculations and agree, in most cases, very well with experimental values. However, most processes of the living world and chemical reactions proceed *via* excited states. At present very little is known about the structures of excited states and few excited state structures have been determined so far (*e.g.* Collet *et al.*, 2003; Vorontsov *et al.*, 2005; Gawelda *et al.*, 2007; Pham *et al.*, 2007; Bressler *et al.*, 2009). However, the knowledge of these excited state structures is a critical issue to fully understand the physical and chemical properties of particular compounds, and many quantum chemical predictions fail because of this missing information.

1.1. Pump and probe experiments

X-ray diffraction and X-ray spectroscopy, especially at modern third-generation synchrotron sources, are very powerful experimental methods for exploring excited state structures. For time-resolved experiments at synchrotrons, with time resolution in the picosecond to microsecond range, the sample is mostly excited by a laser light pulse (pump) and then subsequently probed with an X-ray pulse arriving with a certain delay time with respect to this pump pulse. Sample excitation is, however, not limited to laser illumination, and other excitation sources like alternating electric and magnetic fields have also been applied successfully (Vogel *et al.*, 2004; Raabe *et al.*, 2005; Quitmann *et al.*, 2008, and references

therein). Such pump and probe experiments ideally require fully reversible processes or continuous sample replacement because of the limited information that can be gained from a single shot – even at very brilliant synchrotron sources. By using repetitive measurements adequate signal to noise ratios can be obtained.

1.2. Current chopper designs

An experimental difficulty of such pump and probe experiments is the high X-ray repetition rate at current synchrotrons, in the several hundred kilohertz to the several hundred megahertz range, and the much lower pump frequencies of the optical lasers – typically in the few kilohertz range. Currently two different techniques are applied to solve this problem. One possibility is the use of very fast detectors with readout times in the nanosecond range or gated detectors. Here only the X-rays directly following the pump pulse are counted and the radiation arriving later is not taken into account. Drawbacks of this approach are radiation damage to the sample, which is continuously exposed to the full beam, and the limitations in the choice of the detector; for example, most integrating two-dimensional detectors like CCDs cannot be used. A very promising approach for using two-dimensional detectors for time-resolved experiments is the gating option of the Pilatus pixel detector (Broennimann *et al.*, 2006).

Another option to match the pump frequency with that of the X-ray pulses and at the same time to drastically reduce the radiation damage to the sample is the use of a so-called chopper. A chopper absorbs the unwanted X-ray pulses and only the selected pulses following the pump pulse are trans-

mitted through small openings in a wheel or reflected by a crystal. Different chopper designs, such as fast rotating reflecting crystals and piezo-switchable reflecting crystals, have been tried (Grigoriev *et al.*, 2006; McPherson *et al.*, 2000). However, the only routinely used X-ray chopper system capable of single-bunch extraction is the so called Jülich chopper (Wulff *et al.*, 2003). It is based on a directly servo-motor-driven triangular rotor with a magnetic bearing and operated in vacuum. Currently its repetition rate is limited to about 900 Hz with an upgrade option to 2700 Hz.

2. Chopper design parameters

It was the goal of this work to develop a chopper system capable of extracting X-rays generated from a single bunch of the PETRA III storage ring and the camshaft pulse from the hybrid timing structure of the Swiss Light Source (SLS). The PETRA III storage ring will be operated about half of the time with a very dense filling pattern and the other half in a 40-bunch mode with a bunch-separation time of 192 ns. Thus the extraction of single bunches requires an opening time of less than 384 ns with a very small jitter. In addition, the system should be capable of extracting single bunches with different repetition rates, *e.g.* 500 and 1000 Hz. For a first version of the chopper system a rotation frequency of 500 Hz was chosen. Isolation of the camshaft pulse at the SLS requires an opening time of less than 180 ns, which can be realized only at rotation frequencies higher than 500 Hz and should be met in an improved version of the device, currently under development.

2.1. Chopper wheel

The opening time t of a slit with width w in a chopper wheel at the radius r rotating at frequency f is given by

$$t = w / (2\pi r f). \quad (1)$$

For experiments, a large slit width w , to accept most of the X-ray beam, and a short opening time, t , to extract single bunches, is desirable. Theoretically the use of chopper wheels with large radii would ideally fulfil these requirements. However, larger diameters have the disadvantage of a higher mass of the chopper wheel, which requires much stronger and larger bearings and also induces much stronger strain inside the chopper wheel, eventually causing it to fail. A chopper wheel with a diameter of 150 mm, a slit width of 50 μm and a rotation frequency of 500 Hz were chosen for this device. In our calculation these parameters turned out to be the optimal compromise.

Since rotation frequencies of 500 Hz at a diameter of 150 mm already induce large amounts of strain in the wheel, finite element (FE) calculations were performed to optimize the chopper wheel geometry. To reduce unfavourable stress occurring at rotation frequencies at 500 Hz and higher, mainly at the centre of the wheel, the wheel thickness increases from 4 mm at the outer diameter to 8 mm close to its centre. Heat-treated chromium steel (1.4034, yield strength > 1.8 GPa) was chosen as the disc material, since it provides a very good X-ray

attenuation to density and tensile strength ratio. With a thickness of 4 mm at the outer diameter, where the X-rays are incident on the material, an attenuation coefficient of less than 10^{-10} for 25 keV X-rays is obtained.

2.2. Slit design

The slit design was also optimized by FE methods. The classical slit design with notches on the outer diameter turned out to be sub-optimal. Especially at rotation frequencies higher than 500 Hz, these notches would expand at their outer end, thereby inducing large amounts of stress at the inner end, which would finally cause the wheel to fail. Our FE calculations led to an optimized slit design. To obtain a homogenous slit elongation the slits are moved away from the edge and are now placed between two elliptical holes, which further reduce the stress due to the increased bending radius in the radial direction (see Fig. 1*a*). For a 1000 Hz rotation frequency a slit expansion of about 11 μm is predicted. Placing one slit at a radius of 68 mm and two slits separated by 180° at a radius of 70 mm allows the realization of two different chopping frequencies of 500 and 1000 Hz, respectively, on the same chopper wheel with only slightly different opening times. Manufacturing of the slits with electrical discharge machining (EDM) was very successful. Micrographs of the slits reveal a homogeneous slit width and a minimal roughness (see Fig. 1*b*).

2.3. Encoder system

Synchronization of the chopper rotation to the synchrotron ring frequency requires the precise detection of the chopper speed and its phase. Since no high-accuracy encoder system applicable at $30\,000\text{ r min}^{-1}$ was commercially available to us, we decided to develop our own fast light-guide system for phase and speed detection of the chopper wheel. Here the light coming from a laser diode (550 nm) passes through the same 50 μm slit as the X-rays – but at the opposite side, which means at a phase angle of 180° . The light signal is detected with a fast Silicon PIN diode attached to an in-house-designed fast amplifier circuit. It was not possible to determine the jitter of the light-guide system independent of other parameters but it is certainly smaller than the jitter of the entire system, which is less than 5 ns. Using the same slit for X-ray transmission and for the control of the system has the advantage of avoiding the introduction of any systematic errors due to thermal drifts or other disturbances, since these affect both signals in the same way.

2.4. Chopper bearing

Precise control of motion, as needed for a fast chopper system, requires a very low friction of the underlying bearing. Magnetic bearings possess no friction, are normally operated in a vacuum environment and should hence be ideally suited for a chopper system. A drawback of magnetic bearings is the relatively large sphere of confusion of these bearings, which require an active magnetic stabilization of the bearing. The remaining eccentricity is normally of the order of a few micrometres and contributes to the jitter of the system.

Further drawbacks are the relatively high costs and the complicated control equipment needed to operate such a system.

Another promising approach is the use of air-bearing technology for chopper systems (McPherson *et al.*, 2000; Gembicky *et al.*, 2005). Air bearings have the drawback of possessing much higher friction compared with magnetic bearings and are difficult to operate in a reduced-pressure environment. The advantages of air bearings are their high stiffness and their intrinsic small sphere of confusion, which is typically in the sub-micrometre range, and they do not require any further positional feedback system. Because of these advantages, and the much lower cost, we decided to use a directly driven air bearing for our chopper system. The power of the three-phase servo motor chosen is 40 W. To reduce

power losses and heating due to air friction of the spinning chopper wheel, the housing of the chopper disc is continuously pumped with a vacuum pump, resulting in a pressure of about 8000 Pa inside the housing. An assembly drawing of the chopper system is shown in Fig. 2.

2.5. Safety precautions

The chopper wheel spinning at 500 Hz stores an enormous amount of kinetic energy, which would be suddenly released in case of device failure. Therefore safety concerns had to be taken into account. Three safety precautions were taken. By far the most probable failure of the device is a collapse of the bearing, for example, by interruption of the air supply. The safety risk mainly arises from the spinning wheel and not from the bearing shaft. Thus it was decided to introduce a predetermined breaking point at the interconnection between wheel and shaft, such that in case of a failure the connection between them is lost and both parts can move independently. In addition the housing is lined with brake pads normally used in automotive engineering (see Fig. 2). The use of brake pads should prevent a sudden stop of the wheel due to, for example, cold welding with the housing. In case of a failure they slowly decelerate the wheel by converting most of the kinetic energy into thermal energy. As a third precaution, the housing of the chopper wheel is made of a particular steel providing a high elongation at fracture.

2.6. Controller

As no commercially available controller was found to meet our requirements it was decided again to develop a new controller system. The analogue controller works with pulse width modulation in a phase lock loop. It adjusts the speed of the chopper wheel in such a way that the time difference between the signal coming from the light guide and the 500 Hz signal derived from the master bunch clock is minimized. A phase shift to exactly match the X-ray arrival time can be generated by introducing a delay time to the signal from the master bunch clock. The controller has three input channels for the divided master bunch clock signal, the signal from the light guide and the signal from the Hall device integrated in the motor, and one output channel for the motor. The housing

(a)

(b)

Figure 1

(a) Predicted stress around the slit position at 1 kHz (from FE calculation) for the slit design realized in the chopper wheel. (b) Micrograph of a 50 μm slit manufactured by wire EDM.

Figure 2

Assembly drawing of the chopper components. The housing consists of the red part, to which the air bearing itself (grey) is mounted through a central hole, and the golden part with windows (blue) to let the X-rays pass through. The brake pads are shown in green and the chopper wheel in yellow.

of the controller is quite compact with dimensions of $20 \times 20 \times 30$ cm.

3. Performance testing

The performance of the chopper system was evaluated at the optics test beamline X05DA at the SLS. The X-rays originating from a super bend dipole magnet were monochromated using an Si 111 double-crystal monochromator and subsequently focused with a toroidal mirror to $80 \times 140 \mu\text{m}$ at FWHM (vertical $\times$ horizontal). The experiments were carried out at an X-ray energy of 12 keV. For the tests, the chopper was mounted at the position of the X-ray focus on two motorized translations to position it vertically and horizontally in the X-ray beam. A beam-defining slit system with an opening of $50 \times 200 \mu\text{m}$ was placed 120 mm before the

chopper. A photograph of the experimental setup is shown in Fig. 3. The transmitted X-rays were detected with a fast silicon photodiode (type: AXUV High-Speed with 700 ps rise time, 1×1 mm sensitive area; manufacturer: IRD) placed about 150 mm behind the chopper. The chopper was synchronized to the one millionth sub-harmonic (500 Hz) of the SLS master bunch clock (500 MHz). Acceleration from 0 to 500 Hz and subsequent phase-lock-in took 120 s. Fig. 4 shows the recorded timing structure of the transmitted X-rays and the SLS timing structure. The peak at about 320 ns arises from the so called 'camshaft' bunch, which is separated by 150 ns in one direction and 30 ns in the other direction from the densely packed multi-bunches, with bunch-separation times of 2 ns which were not resolved with the equipment used (see Fig. 4). The total opening time shown here is about 350 ns. This is due to the fact that the effective opening time is determined by the convolution of the chopper slit size and the vertical beam size, which was about $50 \mu\text{m}$ in our experiment.

Figure 3
Chopper system installed at the optics test beamline X05DA at the SLS. The X-ray beam passes through the Kapton window, which can be seen on the right side of the chopper wheel housing. The two brown tubes are used to evacuate the chopper housing.

Figure 4
Time-averaged intensity profile of the X-ray signal of the chopped X-ray beam measured with a fast Si diode.

4. Conclusion and outlook

The experiments successfully showed that it is possible to realize an opening time of about 220 ns with an excellent long-term jitter of less than 5 ns using air-bearing technology (Fig. 5). The system is capable of extracting X-rays (with energies up to 25 keV) coming from a single bunch of a storage ring and is much less expensive than available chopper systems based on magnetic bearing technology. The chopper is easy to install and to handle owing to its small weight and size and requires only a small controller box.

The current version is limited to a repetition rate of 500 Hz; however, a second version is already under development and the first tests are scheduled for the end of 2009. This second device will be operated at a pressure of less than 10^{-2} Pa. This should allow for higher rotation frequencies of up to 1 kHz owing to reduced gas friction and result in opening times of less than 150 ns. This expands the applicability of the device to

Figure 5
Histogram of the long-term jitter (80 min) measured as the difference between the one millionth sub-harmonic of the SLS master bunch clock (500 MHz) and the encoder signal from the fast light guide.

Figure 6

Experimental setup for a time-resolved pump and probe microcrystallography experiment planned for beamline P11 at the PETRA III storage ring. A focused pump laser beam excites the sample from the top. The sample is subsequently probed with X-rays illuminating the crystal very close to the surface, where a high population density of the excited state is achieved.

other synchrotron sources, such as the SLS, having smaller bunch-separation times than at PETRA III. By increasing the number of slits in the wheel, X-ray pulse repetition rates of up to 100 kHz should be possible.

At the SLS it is planned to use this chopper system in combination with an ultra-fast hard X-ray streak camera. Up to now the isolation of the camshaft pulse has been integrated into the streak camera setup. The delivery of single camshaft pulses is expected to further improve the time resolution of this detection system of currently < 2 ps, thereby allowing for pump–probe experiments with resolutions far beyond the camshaft pulse length of 100 ps.

Ideal locations for such chopper systems are intermediate foci, which are now becoming increasingly popular at third-generation synchrotron beamlines (Evans *et al.*, 2007). Owing to the small vertical beam size at the intermediate focus, most of the X-rays can pass even a tiny slit of $50\ \mu\text{m}$. One chopper system will be installed at the intermediate focus of the ‘Bio-Imaging and Diffraction Beamline P11’ at the PETRA III storage ring for time-resolved microdiffraction experiments as schematically shown in Fig. 6. Such an approach should allow

new types of experiments and require much less laser power since a much smaller crystal volume needs to be excited.

We thank Dr Uwe Flechsig and Markus Willmann for their kind support at the optics beamline 5DA at the Swiss Light Source. We further thank Dr Timo Korhonen for his extremely helpful and fast support at short notice with the timing signal required for the chopper synchronization.

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