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A new high-speed beam chopper for time-resolved X-ray studies

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A new high-speed X-ray beam chopper, which can be phase locked to the temporal structure of the Advanced Photon Source (APS) storage ring, has been developed and tested. The open window time of the chopper is 2450 ns, which corresponds to ~67% of the revolution time of the APS storage ring. By phase locking the rotation of the beam chopper to the storage-ring orbital frequency, any portion of the storage-ring fill pattern can be positioned within the beam-chopper transmission-time window.

Keywords: beam choppers; X-rays; timing; phase locking; synchronization.

1. Introduction

A synchrotron storage ring is a versatile radiation source for time-resolved experiments using X-rays. Typically, the spatial extent of the stored charge within the new third-generation high-brightness sources is only ~3 cm, resulting in X-ray pulses of 100 ps or less. While the X-ray pulses from the new synchrotron sources cannot approach the short-duration X-ray pulses from laser-produced plasmas, within the domain of 100 ps pulses, they do have greater flux per unit solid angle or collimation, and greater tunability than the X-ray pulses produced by the laser-produced plasma sources.

Time-resolved studies utilizing X-ray pulses from storage rings have been important in the study of a variety of physical phenomena (Larson *et al.*, 1982; Mills *et al.*, 1983; Bourgeois *et al.*, 1996; Genick *et al.*, 1997; Coppens, 1997; Harford & Squire, 1997; Rischel *et al.*, 1997; Wulff *et al.*, 1997; Chen *et al.*, 1999). Various techniques have been proposed and employed at synchrotron sources to produce X-ray pulses of varying lengths to match the time scale of these phenomena (Mills, 1989; LeGrand *et al.*, 1989; Norris *et al.*, 1992; Bayer *et al.*, 1992; Wulff *et al.*, 1997; McPherson *et al.*, 1998). Within the synchrotron radiation instrumentation collaborative access team (SRI-CAT) of the Advanced Photon Source (APS), we are developing instrumentation that can take full advantage of a single short X-ray pulse or a pulse train. This instrumentation should allow us to perform time-resolved experiments limited in time resolution only by the temporal structure of the fill pattern of the APS storage ring or, in the case of pulse trains, by the response time of the X-ray detector.

This paper describes the design and performance of a new compact high-speed X-ray beam chopper using laser scanner technology that can be phase locked to the temporal structure of the APS storage ring. In addition, as part of the performance test, a laser pulse was synchronized to the temporal ring structure transmitted through the beam chopper. The ability to phase lock the beam chopper and the synchronization of the laser pulse demonstrates that experiments with time resolution approaching the achievable limit at the APS are possible.

2. High-speed beam-chopper description

The design for this new compact X-ray beam chopper is based upon a commercial high-speed air-bearing laser scanner available from Speedring Systems Inc. of Rochester Hills, Michigan. This beam chopper can be mounted in any orientation and translated or rotated while in operation provided that the translational acceleration does not exceed 0.5g and the slew rate is less than 2 rad s^{-1}. However, the rotation axis cannot be tilted while the beam chopper is in motion because the centrifugal force would damage the air-bearing structure. The manufacturer specifies the operational lifetime of the air bearing as 5000 start-and-stops.

The beam chopper is illustrated in Fig. 1. A compact cylindrical aluminium housing (diameter 99 mm, height 111 mm), sealed and filled with helium to 1 atm, contains the air-bearing shaft that forms the rotating component of the beam chopper. The shaft of the air bearing is a cylindrical rotor made of aluminium that flares into a 5 mm-thick disc. This disc is 50.8 mm in diameter and has a 1 mm-thick coating of nickel around the circumference. The nickel coating ensures an attenuation factor of 10^8 at 30 keV, the maximum X-ray energy planned for use with this beam chopper. A 0.5 mm-wide by 2.29 mm-tall slot (see Fig. 2) was cut through the diameter of the rotor disc to form the opening window of the beam chopper. Both X-ray and visible-light beams may be transmitted through the beam chopper by using two different optical axes, separated by 19.8°, defined by two sets of windows provided on the housing (see Fig. 2). One set of windows is made of BK-7 glass for visible-light transmission, and the other set is 0.23 mm-thick Be for X-ray transmission.

The beam-chopper motor controller is driven by an external frequency derived from the APS storage ring RF frequency, $f_{\rm RF}$, which is supplied ($f_{\rm RF}/1296$) from the accelerator control system. This master clock frequency is sent to a frequency divider that divides it by 51 to produce a frequency of 5324.48 Hz (the precision is determined by the RF frequency from the accelerator control system), which is used as both the driving frequency for the beam-chopper motor controller and the reference frequency for speed regulation. The drive frequency may be varied slightly without harm to the motor. After turn-on of the motor controller the rotor reaches its maximum speed, corresponding to a rotational frequency of ~1331.12 Hz in ~15–20 s. The 0.5 mm-wide slot through the center of the rotor disc produces an open time window lasting ~2450 ns, corresponding to ~67% of the APS storage-ring revolution time. Since the slot is cut through the diameter of the rotor disc, there are two transmission time windows per revolution. The closed time between transmission time windows is ~373 µs.

The principal feature of this beam chopper is the high level of rotor speed regulation. The rotor disc has four polished facets equally spaced around the circumference, hence the need for a driving and reference frequency of 5324.48 Hz. An internal optical encoder (notice in Fig. 1 the small cylinder extending from the beam-chopper housing) reflects an optical beam from these facets and feeds the frequency to a speed control circuit contained on the motor controller board. Feedback to the driver circuit then regulates the rotor speed. The manufacturer has measured the revolution-to-revolution noise, or jitter, in the rotational speed of the rotor of this beam chopper in a performance test. They recorded the time necessary to make a complete revolution of the rotor by measuring the frequency shift between the optical encoder signal (*i.e.* the rotation frequency) and the reference frequency driving the motor. After 5632 samplings, the rotation time was determined to be 751.2469487 µs with a standard deviation of 991 ps. Thus at the 95% confidence level (or 3 standard deviations), the jitter in the opening time window position of the beam chopper is only 3 ns. In no case during the sampling test was the jitter in the rotational time observed to be greater than 5 ns.

3. Performance test of the high-speed X-ray beam chopper

Two operational tests have been performed to demonstrate the timing capabilities of the beam chopper. The first test was to phase lock the rotational motion of the beam chopper rotor to the orbital frequency of the storage ring. For the second test a laser pulse was synchronized to any specified part of the temporal structure of the X-rays transmitted through the beam chopper. A block diagram of the experimental setup used for these two tests is illustrated in Fig. 3.

These operational tests were carried out at the 1-BM-B radiation enclosure at the APS. The APS storage ring has 1296 stable orbital positions (so-called buckets) for storing charge. The separation between buckets is 2.841 ns, but the charge is stored only within the center 100 ps. A typical loading pattern for the storage ring is a sextet (charge stored in six adjacent buckets) followed by a series of triplets (charge stored in three adjacent buckets) or singlets spaced about every 100 ns. Hence the radiative output of the storage ring is not continuous but is a pulsed source. During operation any bucket may be filled or left empty to create various time structures for the radiative output (Mills, 1989; Coppens, 1997; Wulff *et al.*, 1997). During the tests of this beam chopper the APS storage ring was filled with a sextet followed by a triplet sequence of 25 groups of three consecutively filled buckets repeating every 36 buckets. The gap between the sextet and the first triplet consisted of 66 empty buckets, and the gap between triplets consisted of 33 empty buckets. Since this fill pattern does not cover the entire ring space, there is a gap of 357 empty buckets between the last triplet and the sextet.

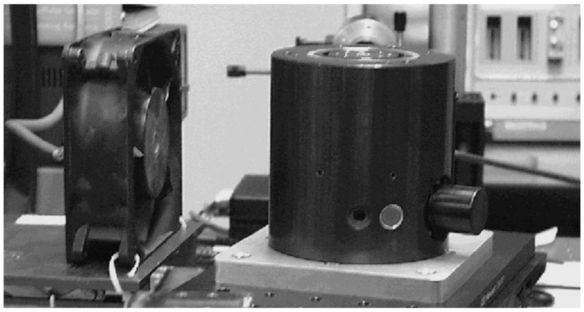

Figure 1
High-speed beam chopper showing the small size of the housing. The reader is looking at the two sets of windows within the housing. On the right-hand side of the housing is an optical encoder that supplies the optical feedback for the motor speed regulation. For the present model a small fan must be used to cool the aluminium housing.

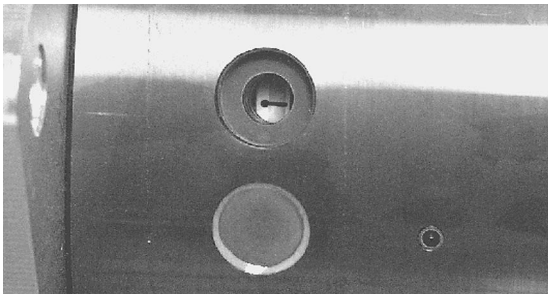

Figure 2
Shape of the slot through the rotor disc is shown in the visible-light window. The keyhole shape was necessary for manufacturing ease in cutting the 0.51 mm-wide slot through the 50.8 mm-diameter of the rotor disc. The top of the key is not included in the 2.29 mm height dimension. A nickel coating covers the disc circumference.

The X-ray beam was first reflected off a collimating mirror to reduce the high-energy content (cutoff at ~24 keV) and to improve the collimation. A pair of Si(111) crystals then monochromated the beam to 8 keV. The second crystal was bent slightly to sagittally focus the X-ray beam to ~1 mm horizontally. The beam chopper was mounted on a goniometer with its rotating axis in the horizontal plane and perpendicular to the X-ray beam, *i.e.* the beam-chopper slit was in the vertical plane.

An avalanche photodiode detector (APD) with a temporal resolution of 5 ns was used to observe the temporal structure of the 8 keV X-rays transmitted through the beam chopper's transmission-time window. [Characterization of the APD as an X-ray detector can be found in Baron *et al.* (1997), Toellner *et al.* (1994) and Powell *et al.* (1999)]. The signal was recorded on a digital oscilloscope (Tektronix model 754A) in a time-averaged mode of 100 trigger events (see Figs. 4 and 5). The 5 ns resolution of the APD prevents the internal structure of the sextet and the triplet from being resolved. The third-harmonic output from a Nd:Yag laser (Spectra-Physics GCR-170) firing at ~10 Hz was detected by a fast (8 ns) Newport photodiode and used to trigger the oscilloscope. A frequency divider, which was built in-house, running off the APS control-room master clock, is used to supply the drive frequency for the beam-chopper motor controller and the trigger signal for the laser. Since the beam-chopper drive frequency is derived from the storage-ring master clock, phase locking was immediate. A delay generator (Stanford model 535) was used to shift the phase between the rotor rotation and the storage-ring orbital frequency. The phase could be adjusted by delaying the beam-chopper drive frequency in steps up to 100 ns without loss of phase locking. Another delay generator was used to shift the phase of the synchronization of the laser pulse to any part of the transmitted X-ray beam. The results of both tests are summarized in Fig. 4. As illustrated, the transmission window was positioned such that the sextet was just visible. With 23 triplets being observed, the transmission window open time can be estimated to be 2450 ± 50 ns. [The estimated uncertainty in the transmission window open time is due to the spacing between the triplets in the storage ring used for this measurement, rather than any jitter in the motor operation.] The integrated area under each peak represents the number of photons recorded for the sextet and each observed triplet. Since the vertical size of the X-ray beam is larger than the width of the beam-chopper slit, the profile of the transmitted ring structure (*i.e.* the transmission function) is triangular.

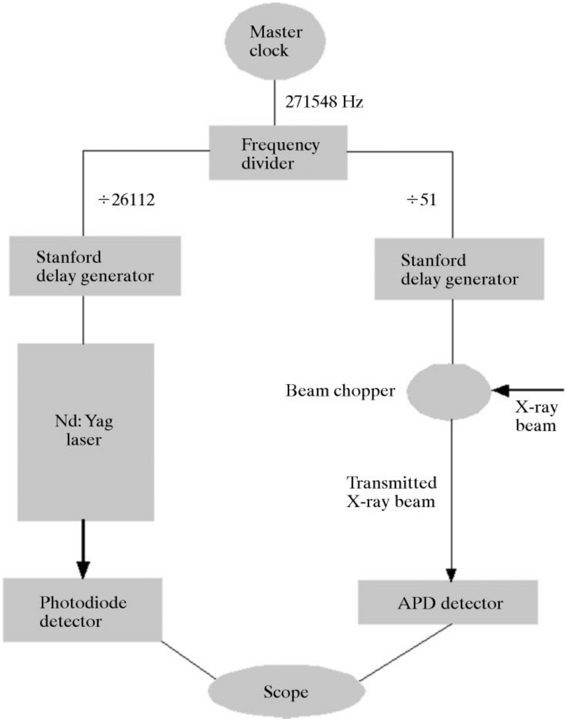

Figure 3
Experimental layout for testing both the phase locking of the beam-chopper rotor rotation to the orbital frequency of the storage ring and the synchronization of a laser pulse to the temporal structure of the X-ray pulse transmitted through the beam chopper.

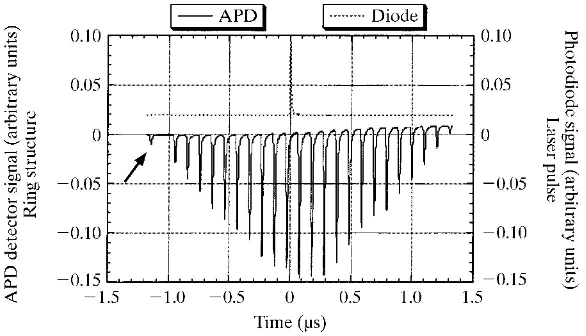

Figure 4
A digital oscilloscope was used to record the phase locking of the beam chopper and the synchronization of a laser pulse to the X-ray temporal structure of the APS storage ring. The sextet, indicated by the arrow, is just visible through the transmission-time window. The ability to phase lock the rotation of the beam-chopper rotor to the orbital frequency of the storage ring allows for data collection without noticeable jitter in the recorded temporal structure of the ring loading pattern. The laser signal, positioned after the tenth triplet, was used as the scope trigger.

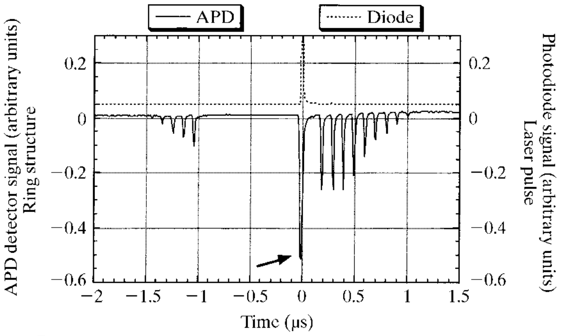

Figure 5
A different portion of the X-ray pattern of the storage ring is transmitted through the beam-chopper transmission window, and a laser pulse is synchronized to the sextet, indicated by the arrow.

By delaying the drive frequency to the beam-chopper motor controller, any part of the storage-ring fill pattern can be sent through the beam-chopper transmission window. Adjusting the delay to the laser trigger then allows synchronization of the laser pulse to a different section of the X-ray time structure, as illustrated in Fig. 5. Again, by monitoring the known temporal structure of the X-rays transmitted through the rotor slot, the transmission-time window is consistently estimated to be 2450 ± 50 ns, or slightly above the design goal of an opening time of 2400 ns. Several measurements indicate that the nickel coating at the edge of the slot may be allowing radiation leakage at the higher X-ray energies (for example, some 24 keV radiation is present in the beam). However, this leakage appears to be occurring only over a distance of $\sim$25 µm from the edge of the slot.

4. Conclusions

The new compact high-speed X-ray beam chopper and measurements described above demonstrate the capability of performing short X-ray pulse time-resolved measurements at SRI-CAT at the APS. The minimum time structure, and hence the maximum time-resolution capability, can be achieved at the APS when X-rays from only one bucket are transmitted through the beam-chopper transmission-time window per opening. At the APS this is possible when the storage ring is filled in an asymmetric pattern in which one filled bucket (of 100 ps width) is centered in two-thirds of the ring and the remaining charge is stored in the remaining one-third of the ring (Mills, 1989). With additional instrumentation, such as photodiodes, APDs, CCD and X-ray streak cameras (Chang *et al.*, 1996) or beam choppers having longer opening times, experiments spanning the time scales from several seconds to $\sim$100 ps can be conducted at the APS.

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