PSEUDO SINGLE BUNCH WITH ADJUSTABLE FREQUENCY*

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Abstract

We present the concept and results of pseudo-single bunch (PSB) operation - a new operational mode at the Advanced Light Source (ALS) - that can greatly expand the capabilities of synchrotron light sources to carry out dynamics and time-of-flight experiments. In PSB operation, a single electron bunch is displaced transversely from the other electron bunches using a short pulse, high repetition rate kicker magnet. Experiments that require light emitted only from a single bunch can stop the light emitted from the other bunches using a collimator. Other beamlines will only see a small reduction in flux due to the displaced bunch. As a result, PSB eliminates the need to schedule multi-bunch and timing experiments during different running periods. Furthermore, the time spacing of PSB pulses can be adjusted from milliseconds to microseconds with a novel "kick-and-cancel" scheme, which can significantly alleviate complications of using high power choppers and substantially reduce the rate of sample damage.

INTRODUCTION

A major limitation of synchrotron light sources is the ability to easily serve two classes of experiments simultaneously, namely, brightness or flux limited experiments and timing experiments. High brightness experiments require filling most of the rf buckets with electrons, thus maximizing the total current while minimizing the current per bunch. In such a multibunch filling pattern, the bunch spacing is typically only a few nanoseconds between electron bunches. On the other hand, timing experiments require longer times between x-ray pulses. For example, in the case of laser-pump x-ray-probe timing experiments, it is desirable to have only one x-ray pulse per laser pulse. Since such lasers operate between kHz and MHz rates, this implies a distance between pulses of ms to μs.

At the Advanced Light Source (ALS) facility, we have been exploring a new mode of operation that we call pseudo-single-bunch (PSB) operation, the goals of which are to allow multibunch and timing experiments to run simultaneously [1, 2, 3]. The idea behind PSB operation is to use a high-repetition (MHz)-rate, short-pulse (<100 ns) kicker [4] to vertically displace a single camshaft bunch relative to the bunch train. Experiments that require light emitted only from a single bunch can block the light emitted from the other bunches using a collimator with only light from the camshaft bunch reaching the experiment. The PSB timing could be at the orbital period (656 ns) or longer, depending upon how frequently the bunch is displaced.

Here we discuss the results of our studies on the PSB operational mode, especially the novel kick-and-cancel (KAC) scheme that can deliver a single pulse with adjustable frequency [3]. A similar idea was previously suggested [5], but to our knowledge this is the first time that it has been realized.

KICK-AND-CANCEL SCHEME

The idea of the KAC scheme is that by adjusting the ring tune and the PSB kick pattern, the camshaft bunch can first be displaced to a different orbit and then kicked back to its original one within a few turns. This KAC process can be repeated at will to create a PSB pulse with an adjustable repetition rate. Mathematically, the KAC scheme can be shown as follows. Assuming that a camshaft bunch is kicked at the i^{th} turn with a kick angle of θ_y, the orbit offset and angle at the n^{th} turn due to this kick are given by

$$\begin{aligned} y_n^i &= \theta_y \beta_y \sin[2\pi(n-i)\nu_y], \\ y_n'^i &= \theta_y \{\cos[2\pi(n-i)\nu_y] - \alpha_y \sin[2\pi(n-i)\nu_y]\}. \end{aligned} \quad (1)$$

To restore the orbit after the n^{th} turn, the superpositions of orbit offsets and angles from each kick need to be zero, i.e.,

$$\sum_{i=0}^{n} y_n^i = 0, \qquad \sum_{i=0}^{n} y_n'^i = 0. \quad (2)$$

Using the two equations above, we can solve the required vertical tune for given number of kicks and orbit turns. There are many possible solutions to Eq. (2). Just one example is presented here. In this example we wish to restore the orbit after two turns within two kicks. The orbit offsets and angles are created by these two kicks at the 2^{th} turn are

$$\begin{aligned} y_2^0 = \theta_y^0 \beta_y \sin 4\pi\nu_y, y_2'^0 &= \theta_y(\cos 4\pi\nu_y - \alpha_y \sin 4\pi\nu_y) \\ y_2^2 = 0, y_2'^2 &= \theta_y^0. \end{aligned} \quad (3)$$

Applying Eq. (2), we can solve the vertical tune $\nu_y = 0.25$.

To test this scheme at the ALS, the vertical tune of the storage ring needs to be adjusted to 9.25 from the nominal tune of 9.20. Figure 1 shows simulated beam orbits for this KAC scheme with the kick angle of 73 μrad. We can see that the beam orbit is displaced for two turns and then kicked back to the nominal one. For example, at the undulator beam line 6.0.1 as indicated in Fig. 1(c), the two orbits are displaced on both sides of the unkicked one, and

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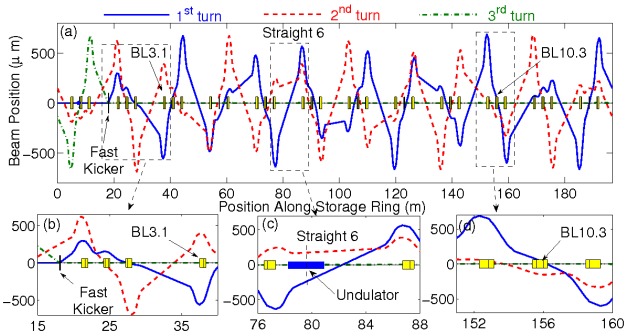

Figure 1: Orbits of the camshaft bunch for kick-and-cancel PSB operation mode at vertical tune 9.25 and kick angle θy=73 μrad: (a) Full 12 sectors; (b) close-up of sectors 2 and 3, where the kicker and beam line 3.1 are located. At the source point of beam line 3.1, the beam is displaced by -560 μm on the 1st turn and 395 μm on the 2nd turn; (c) close-up of straight 6. In the center of the insertion device the beam is displaced by -113 μm on the 1st turn and 188 μm on the 2nd turn; (d) close-up of beam line 10.3 source point. The beam is displaced by 10 μm on the 1st turn and -154 μm on the 2nd turn.

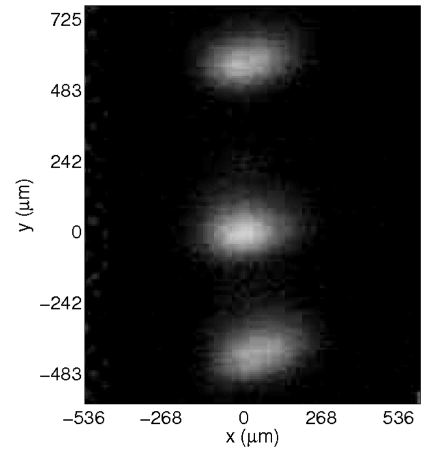

Figure 2: Beam image measurement at synchrotron diagnostic beam line 3.1. For this measurement, the storage ring was filled with a 5 mA single camshaft bunch, and the beam was kicked at the maximum kick-and-cancel frequency.

the maximum separation between them is about 250 μm at the center of the 6.0.1 insertion device.

It should be pointed out that the KAC may affect beam orbit stability through fluctuations of the kick amplitude, and affect the beam size by chromaticity and tune shift with amplitude. The reproducibility of the kick amplitude depends on the stability of the power supply. Measurements using an analog oscilloscope show that the relative fluctuations are approximately 2x10^{-3}, which gives rise to about 0.5 μm orbit motion (about 4% of the beam size). We have also carried out simulations using our accelerator modeling code to estimate the effects of chromaticity and tune shift with amplitude. The results show that beam size growth due to these effects is about 0.5 μm (rms) which is the same as the one caused by the fluctuations of the kick amplitude. These estimates indicate that for the ALS parameters beam orbit motion and beam size increase due to the KAC scheme should be acceptably small.

EXPERIMENTAL TESTS

We first tested this novel operation mode at our synchrotron diagnostic beam line 3.1. At this beam line, the x-ray pulse emitted from the bend magnet is first converted to visible light by a BGO crystal, and then imaged on a CCD camera. Figure 2 shows the measured beam image when the kicker is turned on. Clearly, there are three beam spots, the central one corresponding the un-kicked orbit and the other two the kicked orbits. The separation between the two kicked orbits is about 950 μm, which is consistent with the simulation. For this measurement, the storage ring was filled with a 5 mA single camshaft bunch, and the beam was kicked at the maximum kick-and-cancel frequency, i.e., there is no waiting period between each KAC process. Therefore, the three orbits have the same repetition rate of 500 kHz and the same current of 5/3 mA.

We tested this KAC operation mode at the bend magnet beam line 10.3.2. For this beam line, a side-deflecting toroid mirror forms a 1:1 image of the x-ray beam on a slit. The time-averaged x-ray intensity is measured using a YAG scintillator after the slit, the light from which is detected by a PIN diode. Figure 3 shows the x-ray signals by vertically scanning the slit when the kicker is turned on and off. For these measurements, the storage ring was filled with a 350 mA multibunch train and a 4 mA camshaft bunch. In the figure, the signal from the kicked camshaft is clearly seen on the shoulder of the main bunch background when the kicker is turned on. The signal to background ratio is about 10:1. Compared to the normal operation mode, the background from the main bunch train is suppressed by a factor of about 2500. The separation between the kicked camshaft signal and the main bunch peak is about 150 μm, which is consistent with the simulation.

We tested the KAC scheme at beam line 6.0.1 using a gated detector. The setup of the experiment is shown in Fig. 4(Top). For this test, the storage ring was filled with a 276 mA multibunch train and a 5 mA camshaft bunch. The x-ray pulse emitted from the undulator was measured using a gated avalanche photodiode at an end station of the beam line. Two measurements were carried out, one with a 50 μm slit centered on axis, and the other with the slit centered 190 μm off axis. For the on-axis measurement, the x-ray signals from the bunch train and unkicked camshaft bunches are clearly seen in Fig. 4(Middle); however, the pulses from the kicked camshaft bunch are missing for two turns since the camshaft bunch is displaced to different orbits during these two turns and the radiation from them is blocked by the slit. When the slit is moved off axis (up),

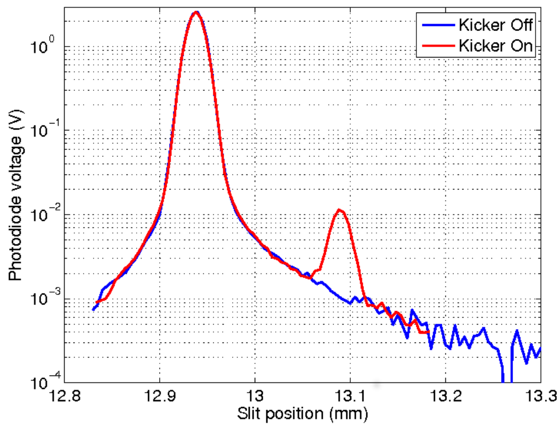

Figure 3: X-ray pulse measurements at a bend magnet beam line 10.3.2 with the kicker on and off. For these measurements, the storage ring was filled with a 350 mA multibunch train and a 4 mA camshaft bunch.

only the radiation from the displaced bunch at the second turn can pass through the slit. Therefore, we only see one pulse in Fig. 4(Bottom).

Finally, we tested this KAC scheme using an integrating (nongated) photodiode at beam line 6.0.1. For this test, the storage ring was filled with the same fill pattern as for the previous test, and the slit was moved off axis to a position where it would optimally transmit the light of the kicked bunch. At this slit position the background signal due to the unkicked bunches was suppressed by 3 orders of magnitude. This large suppression in the signal from the unkicked bunches directly translates to a substantial reduction in the sample damage rate.

CONCLUSIONS AND OUTLOOK

Our results show that with a relatively simple, inexpensive pulsed kicker magnet, it is possible to achieve both single-bunch and multibunch operations at the same time. With the proposed kick-and-cancel scheme, the pulse repetition rate of the PSB photon beam can be adjusted from Hz to MHz, which can significantly alleviate complications of using high-power choppers, substantially reduce the rate of sample damage, and greatly increase the variety and quality of experiments that can be done without using gated detectors.

Recently, ALS has successfully finished brightness upgrade [6]. The nominal working point of the storage ring lattice has been adjusted from the past (14.25, 9.20) to the current (16.25, 9.20). To make this KAC scheme available for beam users, we are planning to increase the vertical tune to 9.25. Horizontal tune scan has been carried out. The lattice with the tune of (16.18, 9.25) seems to be a very good candidate in terms of lifetime, injection efficiency and nonlinear beam dynamics. Further studies are undergoing to test this lattice and results look very promising. At this new working point, we could operate this KAC scheme during the normal operation, which would eventually allow to run

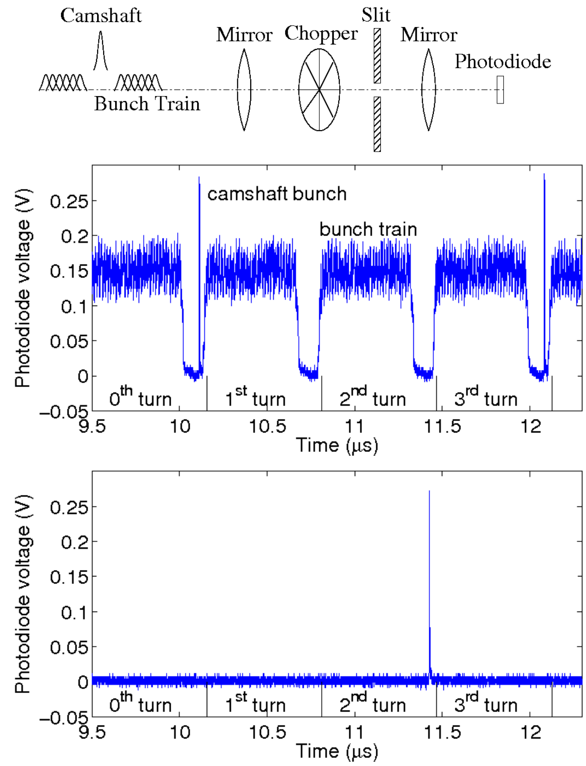

Figure 4: X-ray pulse measurements at an undulator beam line 6.0.1. (Top) Experiment setup; (Middle) On-axis measurement. The 50 μm slit is centered on axis. (Bottom) Off-axis measurement. The slit is off axis by 190 μm.

brightness and timing experiments simultaneously.

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REFERENCES

[1] G. Portmann *et al.*, in *Proceedings of PAC07, Albuquerque, NM, USA, 2007* (IEEE, Albuquerque, NM), pp. 1182-1184.

[2] G. Portmann *et al.*, in *Proceedings of the Beam Instrumentation Workshop, Tahoe City, CA, 2008*, pp. 213-217.

[3] C. Sun, G. Portmann, M. Hertlein, J. Kirz, and D.S. Robin, Phys. Rev. Lett. 109, 264801 (2012).

[4] S. Kwiatkowski *et. al.*, in *Proceedings of EPAC06, Edinburgh, Scotland, 2006*, pp. 3547-3549.

[5] L. Blumberg, "VUV Wobbler", Brookhaven National Laboratory Memorandum, May 29, 1980.

[6] C. Steier *et al.*, in *Proceedings of PAC13, Pasadena, CA, USA, 2013*, TUOCB2.

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