Pseudo-Single-Bunch with Adjustable Frequency: A New Operation Mode for Synchrotron Light Sources

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We present the concept and results of pseudo-single-bunch (PSB) operation—a new operational mode at the advanced light source—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 beam lines will only see a small reduction in flux due to the displaced bunch. As a result, PSB eliminates the need to schedule multibunch 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.

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The success of storage ring based synchrotron light sources is due in large part to the ability to simultaneously serve multiple users with a diverse set of requirements such as high-photon flux and brightness, large range of wavelengths, variable polarization, and relatively short (10–80 ps) pulses. A major limitation of synchrotron light sources is the inability to serve two classes of experiments simultaneously, namely, brightness or flux limited experiments and timing experiments. High brightness operation requires 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.

For timing experiments, synchrotron light sources occasionally operate in a low current few-bunch mode. In such a few-bunch mode, the maximum spacing between x-ray pulses is a few hundred ns to a μs, being limited by the storage ring orbital period. The Advanced Light Source (ALS) operates about 10% of the time in a lower current (35 mA) two-bunch mode [see Fig. 1(a)] where two electron bunches circulate on opposite sides of the ring spaced by 328 ns. The ALS operates 90% of the time in a brightness optimized high-current (500 mA), multibunch mode [see Fig. 1(b)]. In this mode, a train of 276 (out of a possible 328) buckets are filled with electrons, with a gap of 100 ns where an isolated camshaft bunch is filled with 5 mA.

The concept of using a camshaft bunch in multibunch operations started many years ago and originated out of the desire for some timing experimenters to operate during multibunch mode. However, most timing users can not use the camshaft due to the short 100 ns gap. The ones that do must use gated detectors or expensive mechanical choppers to reduce the background from unwanted bunches. These choppers are challenging to fabricate and operate, and for beam lines that operate without a monochromator they have to absorb about a kW of power while rotating at high speeds. Furthermore, the rotating frequencies of choppers constrain the repetition rate of the external laser.

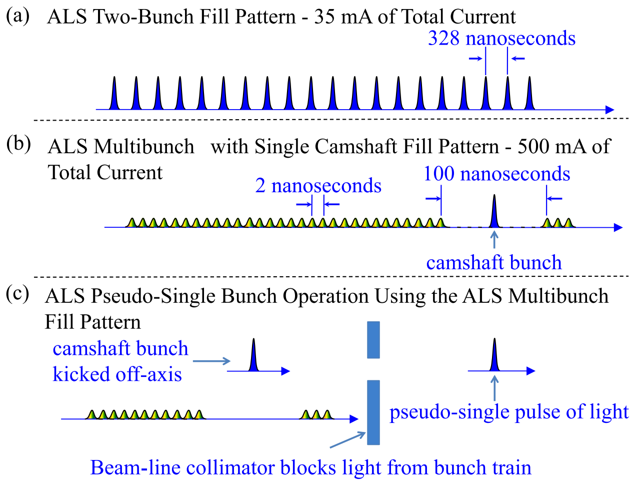

FIG. 1 (color online). ALS fill patterns and pseudo-single-bunch operation: (a) 35 mA two bunch, (b) 500 mA multibunch with single 5 mA camshaft, (c) pseudo-single pulse of light generated when collimating all light except that emitted from the displaced camshaft bunch.

Recently at the ALS, 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 [1–3], and to alleviate complications of using high-power choppers. The idea behind PSB operation is to use a high-repetition (MHz)-rate, short-pulse (<100 ns) kicker to vertically displace the camshaft bunch relative to the bunch train. Then, by collimating the light from the multibunch train in the beam line, only light from the camshaft bunch reaches the experiment. This is illustrated in Fig. 1(c). The PSB timing could be at the orbital period (656 ns) or longer, depending upon how frequently the bunch is displaced.

A similar idea was previously suggested [4], but to our knowledge this is the first time that it has been realized. At the ALS, PSB operation has been demonstrated in various operation forms allowing considerable flexibility. It allows the use of non-gated detectors greatly increasing the variety and quality of experiments that can be done. In this Letter, we discuss the results of our studies on the PSB operational mode, especially the novel ''kick-and-cancel'' (KAC) scheme which could deliver a single pulse with adjustable frequency. In addition to the KAC scheme, PSB can be operated in another fixed high-repetition-rate mode, creating single or multiturn closed orbit displacement. This mode of operation is described in papers [1–3,5].

The ALS is a storage ring light source with 196.8 meter circumference, made up of 12 sectors, each consisting of a 5 meter straight section and a triple bend achromat arc. A short-pulse, high-repetition-rate (up to 1.5 MHz) kicker magnet (PSB kicker) [6] was installed in sector 2. The maximum repetition rate of 1.5 MHz was chosen to match the orbital period of the electrons allowing the kicker to fire each turn. It is capable of delivering up to a 73 μrad kick to the 1.9 GeV camshaft bunch without kicking the multibunch train. The parameters of the storage ring and the PSB kicker are given in Table I. The kicker was designed to kick in the vertical direction to maximize the kick relative to the beam divergence. As seen in the table the vertical beam size and divergence are considerably smaller than those in the horizontal plane. At 73 μrad the kick is about 20 times larger than the vertical beam divergence $\sigma_{y'}$.

Operationally, there are a number of restrictions on the PSB pulser. Neither the kick angle nor kick polarity can be changed quickly. However, the option of a variable kick frequency exists. For instance, the kicker can be adjusted to kick every turn, every nth turn, or even have an uneven kick pattern such as kicking once, then kicking two turns later, waiting 1 ms and repeating. This turns out to be a very important feature for some beam users who would like to see an adjustable pulse repetition rate from several kHz to a few hundreds of kHz.

TABLE I. Relevant parameters of the ALS storage ring and the pseudo-single-bunch kicker. Ring parameters are given at the adjusted tunes.

Parameter		Value
Storage ring		
	Electron energy	1.9 GeV
	Ring circumference	196.8 m
	Horizontal tune, ν_x	14.32[a]
	Vertical tune, ν_y	9.25[b]
At kicker location		
	Horizontal size, σ_x	303.1 μm
	Horizontal divergence, $\sigma_{x'}$	21.2 μrad
	Vertical size, σ_y	13.2 μm
	Vertical divergence, $\sigma_{y'}$	3.8 μrad
	Vertical β-function, β_y	3.46 m
	Vertical α-function, α_y	-0.73
PSB kicker [6]		
	Maximum kick angle	73 μrad
	Kick pulse duration	<100 ns

[a] Adjusted from nominal horizontal tune of $\nu_x = 14.25$.
[b] Adjusted from nominal vertical tune of $\nu_y = 9.2$.

To meet this timing requirement, we recently developed a novel KAC PSB operation mode at the ALS. The idea is that by adjusting the ring tune and the PSB kick pattern, the camshaft bunch can be first displaced to a different orbit and then kicked back to its original one within a few turns. There are many possible solutions to cancel the displaced orbit. Here, we present one example at a quarter integer tune 0.25. In this example we wish to restore the orbit after two turns. Figure 2(a) illustrates this idea in a normalized phase space. The camshaft bunch is first displaced to a different vertical orbit and then proceeds two turns. At the end of the second turn, the bunch has the same vertical offset but the inverse angle to the one after the first kick. At this time, if another identical kick is applied, the bunch will be put back to its original orbit. This KAC process can be repeated at will to create a PSB pulse with an adjustable repetition rate, which is illustrated in Fig. 2(b).

To test this KAC example at the ALS, the vertical tune of the storage ring needs to be adjusted to 9.25 from the nominal tune of 9.2. Figure 3 shows two simulated orbits with the kick angle of 73 μrad. We can see that this

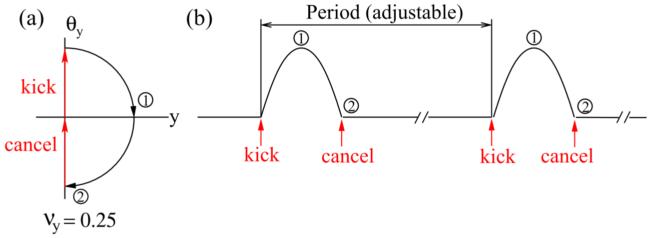

FIG. 2 (color online). Schematic of the kick-and-cancel mode: (a) Phase space, (b) PSB pulses with adjustable frequency.

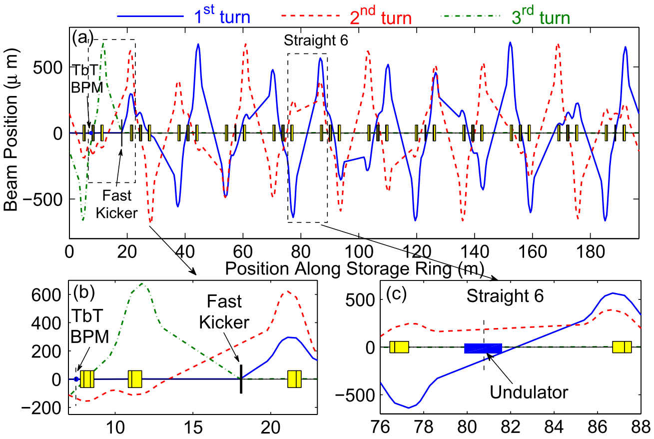

FIG. 3 (color online). Orbits of the camshaft bunch for kick-and-cancel PSB operation mode at vertical tune 9.25 and kick angle $\theta y = 73\ \mu$m: (a) Full 12 sectors, (b) close-up of sectors 1 and 2, where the BPM and kicker are located, (c) close-up of straight 6. At the BPM the beam is displaced by $-140\ \mu$m on the 2nd turn and $-60\ \mu$m on the 3rd turn. In the center of the insertion device in sector 6 the beam is displaced by $-113\ \mu$m on the 1st turn and 188 μm on the 2nd turn.

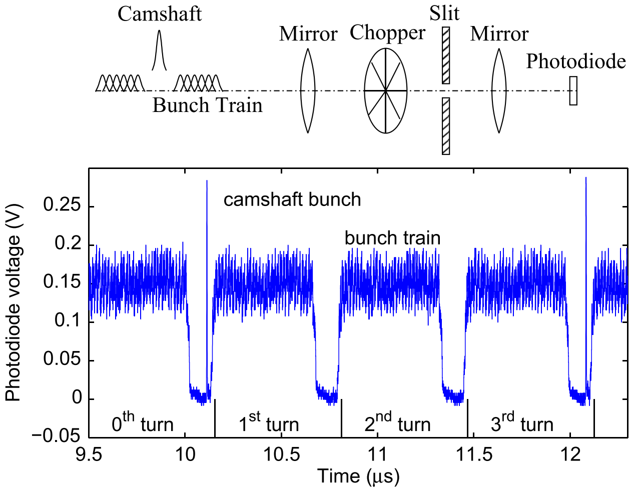

FIG. 5 (color online). On-axis measurements of the x-ray flux for the kick-and-cancel PSB operation mode at an end-station of beam line 6.0.1. The 50 μm slit is centered on axis. The bunch train is on axis on each turn; the camshaft bunch is vertically displaced by 0, -120, $+190$, 0 μm with respect to the axis for turns 0 (before first kick), 1, 2, and 3 (after second kick), respectively; hence, it is stopped by the slit on turns 1 and 2.

scheme is favorable for a number of beam lines. For example, at the undulator beam line 6.0.1 as indicated in Fig. 3(c), the two orbits are displaced on both sides of the unkicked one, and 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 impact 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 2×10^{-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 corresponds to a beam size increase of 4%. These estimates indicate that for the ALS parameters beam orbit motion and beam size increase due to the KAC scheme should be acceptably small.

We first tested this novel operation mode using a turn-by-turn (TBT) beam position monitor (BPM) [7] located in arc 1 as indicated in Fig. 3(b). For test, only a 5 mA single camshaft bunch was filled in the storage ring. The BPM signals are shown in Fig. 4(a), where the PSB pulses with a

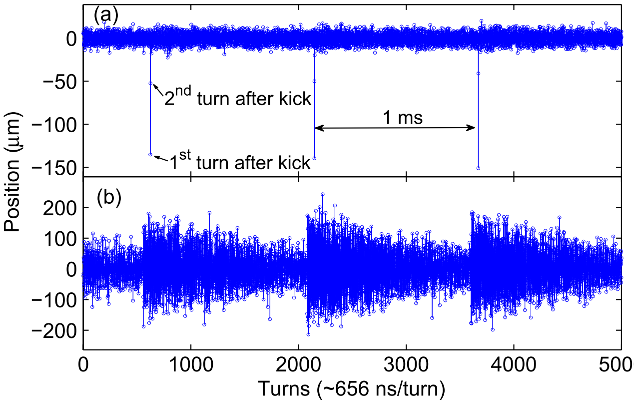

FIG. 4 (color online). Turn-by-Turn BPM signal. The BPM location is indicated in Fig. 3. (a) Kick and cancel, (b) kick without cancel. Note different vertical scales in (a) and (b).

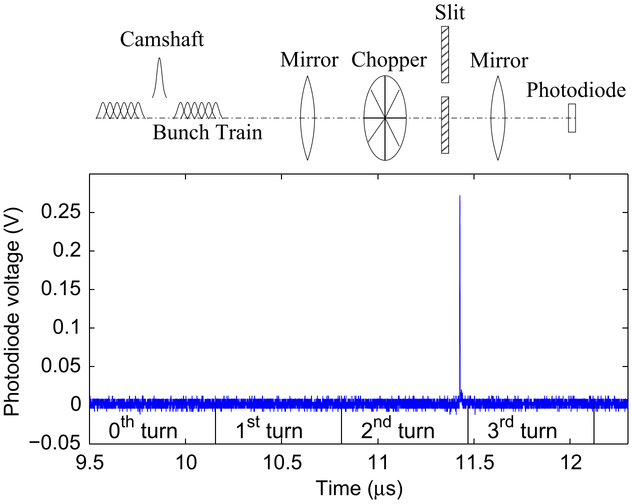

FIG. 6 (color online). Off-axis measurements. The measurement conditions are same as shown in Fig. 5, except the slit is centered 190 μm off axis.

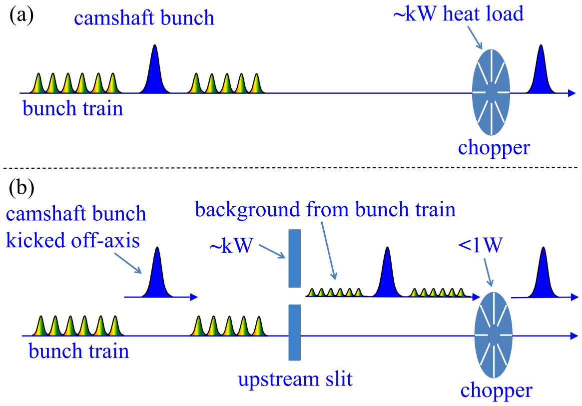

FIG. 7 (color online). Alleviating complication of using high-power choppers. (a) High power chopper for nominal operation, (b) low power chopper for PSB operation.

period of 1 ms are clearly seen. Figure 4(b) shows the BPM signals under the same conditions, however the second kick (the cancel kick) is not applied at the end of the second turn. Clearly, the orbit is not restored to original position. The variation of the beam centroid position in KAC operation estimated from the BPM signal is about 8 μm (rms) which is at the level of the BPM resolution. Measurements at other locations using synchrotron radiation monitors confirm that the beam size growth due to the KAC process is acceptably small and the orbit seems to be stable.

We tested the KAC scheme at beam line 6.0.1 using a gated detector. The setup of the experiment is shown in Figs. 5 and 6. 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. The results are shown in Figs. 5 and 6. Two measurements were carried out, one with a 50 μm slit centered on axis (Fig. 5), and the other with the slit centered 190 μm off axis (Fig. 6). For the on-axis measurement, the x-ray signals from the bunch train and unkicked camshaft bunches are clearly seen in Fig. 5; 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), only the radiation from the displaced bunch at the second turn can pass through the slit. Therefore, we only see one pulse in Fig. 6.

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. While this suppression is impressive in itself, it was only a first attempt and further improvements are possible by increasing the kick amplitude or optimizing the storage ring lattice to reduce the transverse bunch tails. This large suppression in the signal from the unkicked bunches directly translates to a substantial reduction in the sample damage rate.

Beam line 6.0.1 also makes use of a chopper (see Fig. 5, top) that significantly (about factor of 30) suppresses the heat load on the downstream optics by only transmitting a 10 ms window of x-ray pulses at 4 kHz. The chopper also suppresses the background signal during PSB operation by the same factor. However, in regular operation, the total power incident on the chopper is about half a kW—a major technical challenge for chopper design [Fig. 7(a)]. In PSB operation, a slit can be placed upstream of the chopper so that most of the heat load from the beam can be intercepted by the slit rather than the chopper resulting in a considerable simplification for the beam line [Fig. 7(b)]. Low power choppers, located downstream of the slit, may still be desirable for further suppressing the background from the unkicked bunches or adjusting the repetition rates when operating the storage ring for several timing experiments desiring different single bunch frequencies at the same time [8,9].

In conclusion, our results show that with a relatively simple, inexpensive pulsed kicker magnet, that requires only half a meter of a single straight section in the storage ring, it is possible to achieve both single-bunch and multibunch operations at the same time. This greatly expands the capabilities of the light source to satisfy multibunch and timing experiments simultaneously. For more flexibility one can use multiple kickers or kickers that can change the polarity or kick strength. 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. Finally, it is important to mention that although the PSB operation mode was tested at the ALS, this mode is not limited to the ALS and could be adopted at any synchrotron light source facility.

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