

REALIZATION OF PSEUDO SINGLE BUNCH OPERATION 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 beam lines will only see a small reduction in flux due to the displaced bunch. As a result, PSB allows to run timing experiments during the multibunch operation. 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 timing 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 μ s.

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 goal of which is to allow high-flux and timing experiments to run simultaneously [1–4]. The idea behind PSB operation is to use a high-repetition (MHz)-rate, short-pulse (<100 ns) kicker [5] 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

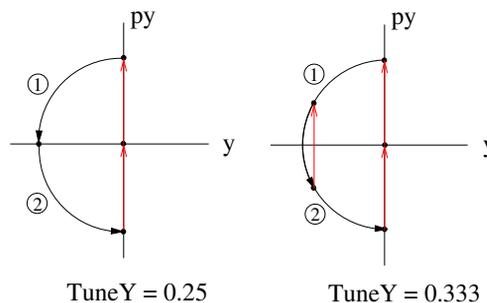


Figure 1: Illustration of the KAC scheme in the phase space at tunes 0.25 and 0.333.

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 [6], but to our knowledge this is the first time that it has been realized.

KICK-AND-CANCEL (KAC) SCHEME

Working Principle

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.

The KAC scheme can be easily understood using a normalized phase space diagram as shown in Fig. 1. In this plot, two schemes are illustrated at tune $\nu_y = 0.25$ and $\nu_y = 0.333$. For example, at tune $\nu_y = 0.25$, 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. Similarly, at $\nu_y = 0.333$, three kicks and three orbital turns are required in order to restore the displaced orbit.

After the beam orbit is restored to the original orbit, we can wait any time of period (KAC period N) and then repeat this kick and cancel process, thus creating single-bunch pulses with adjustable repetition rates.

* Work supported by the Director Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231

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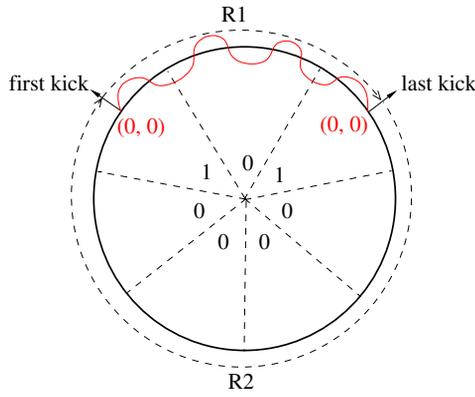


Figure 2: A large multi-turn ring. The vertical tune of the small ring is 0.25. The KAC pattern is KAC101000. Seven rings are concatenated in this example. Two rings with kicker turn-on are labeled with “1”, other rings with kicker off are label with “0”.

Closed Orbit and Resonance Condition

For KAC scheme, the beam is periodically displaced by the kicker. This displacement is actually a stable “closed orbit distortion”(COD). To prove this we first need to construct a large multi-turn ring with a small ring according to the KAC pattern. The number of the small rings made up of the large ring is given by the KAC period N . Let’s look at an example with the vertical tune ν_y of 0.25 as shown in Fig. 2. In this example, the KAC pattern is 1010000 where “1” represents kick and “0” no kick, therefore there are total seven small rings made up of this multi-turn ring and two with kicker turn-on. The ring with kicker turn-on is labeled with “1”, others labeled with “0”. Since the vertical tune of the ring is 0.25 and there are two turns between the first-kick and cancel-kick, the transfer matrix R_1 from the first-kick to the cancel-kick is a negative identity $-I$.

Let’s now look at the closed orbit condition. To find the closed orbit just before the first kick, the following equation needs to be met

$$\begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix} = R_2 \cdot R_k \cdot R_1 \cdot R_k \begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix}, \quad (1)$$

where R_2 is the transfer matrix from the cancel kick to the beginning of the first kick, R_k is the transfer matrix for the kick. Assuming the PSB kick is a thin dipole kick which can only change the beam angle, we can have

$$\begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix} = R_2 \cdot R_1 \begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix}, \quad (2)$$

i.e.,

$$(R_2 \cdot R_1 - I) \begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix} = 0, \quad (3)$$

where $R_2 \cdot R_1$ is just the one turn map of the large multi-turn ring. Eq. (3) is a homogeneous linear equation system. It either has zero solution or infinite solutions which is deter-

mined by the determinant of matrix $|R_2 \cdot R_1 - I|$, i.e.,

$$\begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix} = \begin{cases} 0 & \text{if } |R_2 \cdot R_1 - I| \neq 0; \\ \text{any} & \text{if } |R_2 \cdot R_1 - I| = 0. \end{cases} \quad (4)$$

Assuming the transfer matrix R_2 from the cancel kick to the first kick is

$$R_2 = \begin{pmatrix} E & F \\ G & H \end{pmatrix} \quad (5)$$

and using $R_1 = -I$ and $|R_2| = 1$, we can have

$$|R_2 \cdot R_1 - I| = 2 - (-E - H). \quad (6)$$

Here, $-E - H$ is just the trace of the one turn map of the multi-turn ring, i.e., $-E - H = \text{Tr}(R_2 \cdot R_1) = 2\cos(2\pi N\nu_y)$, where N is the KAC period and $\nu_y = 0.25$ is the vertical tune. Therefore, we can have

$$\begin{pmatrix} y_{co} \\ y'_{co} \end{pmatrix} = \begin{cases} 0 & \text{if } N/4 \neq \text{integer}; \\ \text{any} & \text{if } N/4 = \text{integer}. \end{cases} \quad (7)$$

It is now clear that if $N/4$ is not an integer, the closed orbit (y_{co}, y'_{co}) just before the first kick must be zero, which means the KAC orbit is a stable closed orbit. It has zero displacement outside of the kicks and non-zero oscillation between the kicks as shown in Fig. 2. If $N/4$ is an integer, (y_{co}, y'_{co}) can be any value, which means the KAC orbit is unstable. We need to avoid this resonance condition in order to have a stable KAC orbit.

In general, as $N\nu_y$ approaches an integer, the large multi-turn ring becomes unstable and the KAC orbit is not well defined. Besides this integer resonance, we also need to avoid the following coupling resonances in order to have a stable PSB-KAC operation,

$$m_x(N\nu_x) + m_y(N\nu_y) = n \quad (8)$$

where m_x , m_y and n are integer, N is the KAC period, $N\nu_x$ and $N\nu_y$ are just the horizontal and vertical tunes of the large multi-turn ring. However, these resonances can be easily avoided by adjusting the horizontal tune of the machine away from the resonance [7].

At a stable closed orbit condition, the KAC orbit can be evaluated using an accelerator modeling code. Figure 3 shows the calculated KAC closed orbit for the ALS storage ring at tune (16.16,9.25) with the vertical kick angle of $73 \mu\text{rad}$. We can see that the first kick put the beam to the displaced orbit for two turns, and then the cancel-kick restores the displaced orbit for the rest of the KAC period turns until the next kick. There are three orbits at each location around the ring, two are displaced orbits and one is the design orbit. The orbit separations are different at different location. For example, at synchrotron radiation diagnostic beamline 3.1, the orbits are displaced for about $500 \mu\text{m}$ on both side of the designed orbit.

Decoherence And Stability

Besides the resonance, the KAC beam orbit can also be affected by other factors such as the reproducibility of the

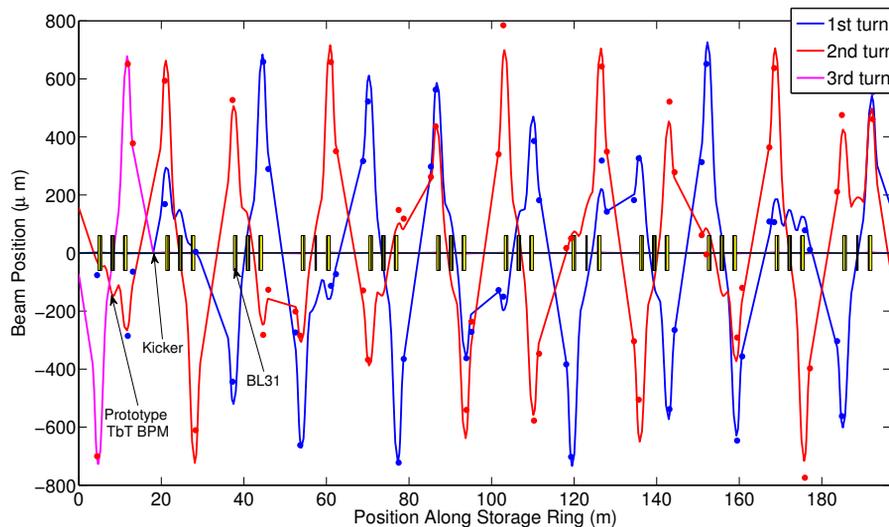


Figure 3: Closed orbit of the KAC beam. The solid curves are the simulation results and dots are Turn-by-Turn BPM measurements .

kick, variation of the machine tune, tune shift with amplitude and chromaticity. These effects can decohere the KAC beam orbit and blow up the beam size if not well controlled.

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 $0.5 \mu\text{m}$ vertical orbit motion. It is only 5% of the vertical beam size (about $10 \mu\text{m}$), which can be neglected.

To restore the displaced orbit, the tune of beam needs to have a correct value and be stable. Tune variations of the beam can cause the residual oscillation of the KAC beam, which can be estimated by $\Delta y = 2\pi\sqrt{\beta_y}\theta_y \cdot \Delta\nu_y$, where β_y is the beta function at the kicker location, θ_y is the kick angle and $\Delta\nu_y$ is the tune variation. There are three major contribution factors to the tune variation, the machine variation (power supply fluctuations and insertion device movements), tune shift with amplitude and chromaticity. A tune feedback system has been implemented at the ALS to stabilize the machine tune variations less than 0.0002. At the ALS, the vertical tune shift with amplitude is about $0.008/\mu\text{-rad}$. The $73 \mu\text{rad}$ kick can cause about $0.02 \mu\text{-rad}$ action amplitude. Therefore the tune shift due to the kick is about 0.00016. The third contribution is the chromaticity effect. Different electron beam with different energy will have different tune. At the ALS, the vertical chromaticity is about 1.4 and RMS energy deviation is about 9.5×10^{-3} which gives the tune variation of about 0.0013. Overall, the total tune variation due to above three factors is about 0.0013, which could result in about $1 \mu\text{m}$ beam motion, which is negligible at ALS. In summary, these estimates indicate that for the ALS parameters beam orbit motion and beam size increase for the KAC scheme should be acceptably small.

KICKER TIMING

Figure 4 shows the schematic of the timing setup for the KAC scheme at tune of 0.25. The external trigger signal can be provided by either beamline users or accelerator users. If the trigger signal comes from the accelerator side, the signal is scaled from a Storage Ring Orbit Clock (SROC) using a Stanford Digital Delay Generator. This trigger signal is fed into a Agilent Arbitrary Waveform Generator to generate two burst pulses. The pulse width is slightly less than one orbital period 656 ns of the storage ring. The distance between two burst pulses is about two orbital turns 1312 ns. These burst pulses are then fed into another Stanford Digital Delay Generator to inhibit the SROC signals. Thus, after the inhibition a KAC signal consisting of two SROCs is created. This KAC signal is then used to trigger the kicker pulser amplifier which further drives the camshaft bunch kicker. The repetition rate of this KAC signal can be easily adjusted by controlling the repetition rate of the external trigger signal.

The advantage of the above timing setup is that the synchronization between the kicks and the electron bunches is independent of the external trigger signal. This synchronization is realized by tuning either the User Timing Control Chassis or the second Stanford Delay Generator. Thus, users have the flexibility to change the timing of their trigger signal without affecting the camshaft kicker timing. This feature is particular important for a stable PSB-KAC operation since the external trigger frequency and timing can be changed by users from time to time.

MEASUREMENTS

At the ALS, various tools and instruments have been utilized to study the Pseudo-Single Bunch Kick-And-Cancel operation mode, including the Turn-by-Turn (TbT) Beam

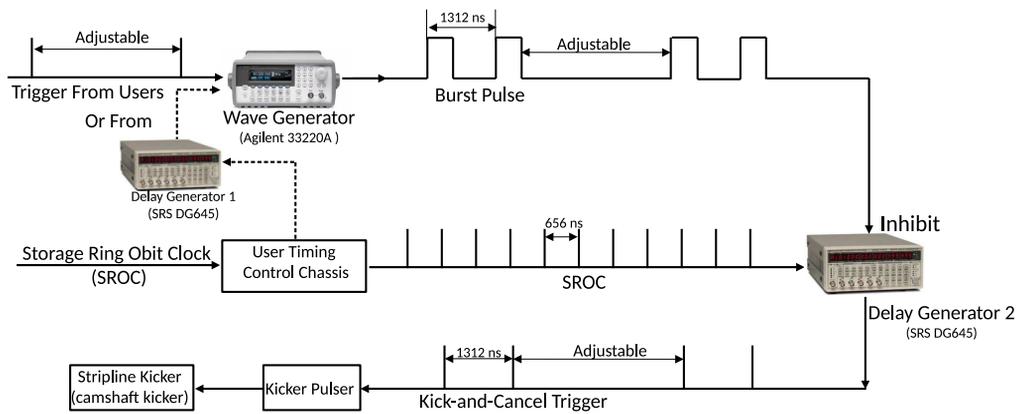


Figure 4: Schematic of timing setup for the Kick-and-Cancel operation mode at tune 0.25.

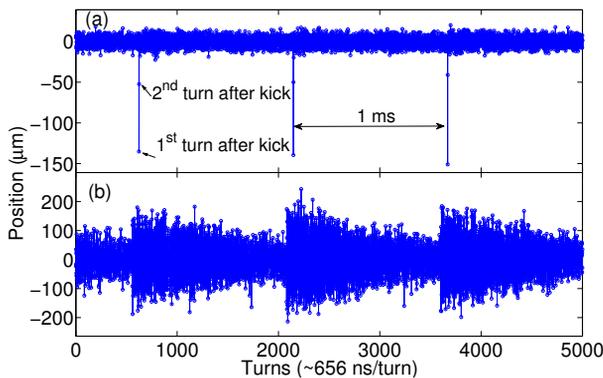


Figure 5: Turn-by-Turn BPM signal. The BPM location is indicated in Fig. 3. (a) Kick and cancel, (b) kick without cancel. Note different vertical scales in (a) and (b).

Position Monitor (BPM), fast-gated and non-gated CCD cameras and bunch-by-bunch transverse feedback system. Each instruments can provide different study aspects on the PSB-KAC, and allows us to better understand this operational mode. In the following, we are going to show the PSB-KAC studies with these tools and instruments.

There are 43 state-of-art TbT BPMs newly installed at the ALS around the storage ring. These BPMs provide a valuable tool to study the KAC scheme in turn-by-turn bases. Figure 3 shows the KAC beam closed orbit measured using these BPMs around the ring, which agrees with the simulation very well. For this measurement, a single bunch 5 mA camshaft bunch is filled in the ring and the kick angle is $73 \mu\text{rad}$.

Figure 5 shows one of our early measurements using prototype NSLS-II TbT BPM located in arc 1 as indicated in Fig. 3. For this measurement, two consecutive bunches (about 10 mA) was filled in the storage ring to improve the signal-to-noise level and the KAC frequency is 1 KHz. As shown in Fig. 5(a), the beam orbit is displaced for two turns after the first-kick and them is immediately restored to the design orbit after the cancel kick. This repeats very 1 ms. Figure 5(b) shows the measurements under the same beam

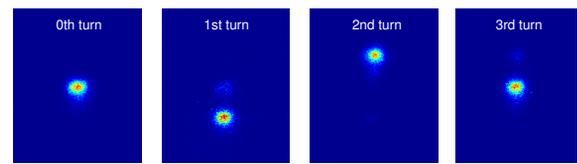


Figure 6: Beam image measurement at synchrotron diagnostic beam line 3.1 with a fast gated camera at different turns after the first kick.

conditions, however the cancel kick is not applied at the end of the second turn after the first kick. We can see that without the cancel kick the displaced beam orbit is not immediately returning back to the design orbit, but slowly damped down through radiation damping effect.

Figure 6 shows a sequence of beam images captured using our fast-gated camera installed at the synchrotron diagnostic beamline 3.1. For this measurement, a single 5 mA bunch is filled in the ring and the KAC frequency is 4 kHz. The camera is triggered by the kicker trigger signal. By adjusting the delay between the trigger and the camera gate opening, we are able to capture beam images at a sequence of turns. The camera gate opening windows is 400 ns at each turn. As we can see, the beam spots are well separated for two displaced turns after the first kick, and then back to the design orbit after the cancel kick. The beam size stays the same during this KAC process.

A scan was carried out to study the resonance conditions at different KAC periods from 3 to 28 as shown in Fig. 7. These beam images are captured by our fast-gated camera but operated in an integrating mode. At lower KAC periods (i.e., the high KAC frequency), the kick orbits repeat at a high repetition rate. Therefore, the kicked beam spots has comparable intensity to the unknicked beam and three beam spots can be clearly seen in the images. As the KAC periods N increased, the intensity of the kicked beam spots become lower and the beam images are dominated by the unknicked beam. For most of the KAC period, we have a stable KAC beam and the beam size is the same to one when the kicker

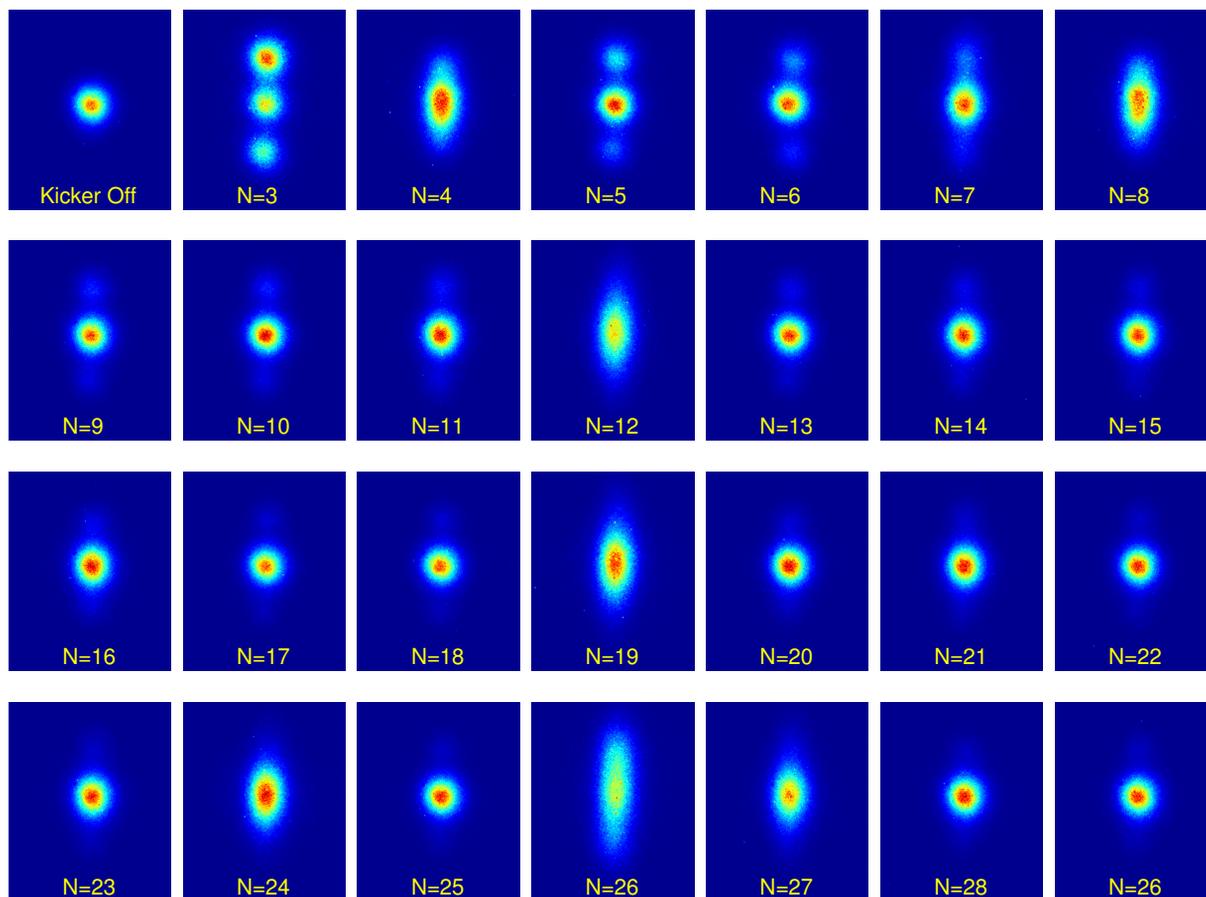


Figure 7: Beam images measured at different KAC period N from 3 to 28. The image at the upper left corner is measured when the camshaft kicker is turned off. The lower right image is a stabilized KAC beam at $N = 26$ by adjusting the horizontal tune of the machine away from the resonance.

is turned off. As expected, when approaching the resonance of the integer multiple of 4, the KAC beams become unstable. The KAC beam are also unstable at some other coupling resonances such as at $N=19, 26$ and 27 . However, at these resonance we can stabilize the KAC beams by slightly adjusting the horizontal tune away from the resonances. The last image (lower right) is a stabilized KAC beam at $N = 26$ after the horizontal tune of the machine is adjusted away from the resonance.

This new PSB-KAC operation mode has also been tested at different x-ray user beamlines at ALS. Results confirm that the radiation light emitted from the kicked camshaft bunch can be well separated from the main bunch train radiation and the background radiation from unwanted bunches can be significantly suppressed [3, 4, 8]. This PSB beams have been used in pump-probe measurements on spin crossover complexes, and in a Warm-Dense-Matter (WDM) demonstration experiment using a time-integrating single-shot streak camera, achieving improved signal to noise while reducing X-ray exposure by three orders of magnitude [8].

CONCLUSION

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.

ACKNOWLEDGMENT

Authors would like to thank S. Kwiatkowski, J. Julian and Ken Baptiste who constructed the PSB kicker and pulser. We also would like to thank beamline scientists M. P. Hertlein, A. Scholl, A. A. Cordones, M. Marcus and T. Tyliszczak who help us test this new operation mode. This work is supported by the Director Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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