Single-pulse measurement of synchrotron radiation using an ultrafast x-ray streak camera

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We have demonstrated that a newly developed, ultrafast x-ray streak camera is sensitive to single x-ray pulses of highly monochromatic and unfocused synchrotron radiation at 8 keV. The high sensitivity was achieved by using CsI as the photocathode material. The individually measured x-ray pulses revealed that the bunch length was 120 ps long (full-width-at-half-maximum) and about 20-30 photon events were registered by streak camera in each pulse at the experimental conditions. The results demonstrated the feasibility of using this streak camera for single-shot experiments and using single x-ray pulses from the third-generation synchrotron sources with microfocused and/or polychromatic beams.

I. INTRODUCTION

There is an increasing interest in obtaining shorter beam bunches and higher peak current for storage rings of synchrotron radiation sources.[1] A streak camera is one of the commonly used detectors for ultrafast x-ray experiments and for characterizing the x-ray pulses, with high temporal and special resolution.[2] With the recent development of third-generation synchrotron radiation sources, such as the Advanced Photon Source (APS), intense hard x-rays have a pulse duration of a few tens of to one hundred picoseconds. This pulse duration may make the single-shot measurement possible, however, due to relatively low peak intensity, most of past and current ultrafast x-ray experiments have been carried out with synchronized accumulative scans using streak cameras with high temporal resolution.[1,3-6] Here, we wish to demonstrate that a single-bunch x-ray pulse can be measured with a high-gain and gated streak camera to facilitate x-ray experiments involving strong scattering and with irreversible transient natures.

II. EXPERIMENT AND RESULTS

The experiment was carried out at the APS MHATT/XOR beamline 7-ID-D, which provided a monochromactic x-ray beam with a flux of about 10^{12} ph/s/mm^2/100mA at 8.0 keV with an energy resolution, $\Delta E/E$, of 1.5×10^{-4}. The APS storage ring has a low natural emittance of 8.2×10^{-9} mrad with 100 mA stored beam current. The nominal bunch length was measured to be between 50 to 100 ps, root-mean-square (rms)[1] by streak camera in the visible regime. An unfocused x-ray beam was used in this experiment with a beam size of 1 (vertical) x 3 (horizontal) mm^2. The streak tube used in this work is the same as that used previously[7,8] except that we used an avalanche transistor sweep circuit instead of a GaAs semiconductor switch. The microchannel plate (MCP) was gated to obtain a better signal-to-noise ratio.

Figure 1 shows a diagram of the experimental setup. The synchrotron radiation from an undulator was used as the x-ray source. A Si(111) double-crystal monochromator was used to produce monochromatic x-ray beam. The incident photon intensity to the streak camera was measured by a nitrogen filled ion chamber. The streak camera was tilted 8° to

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avoid transmitted x-rays directly hitting the MCP, which would cause not only damaged spots but also a high noise level.

The streak camera was synchronized with the x-ray bunches by the trigger signal P0 from the storage ring at 272 kHz, a subharmonic of the accelerator radio frequency (rf), corresponding to the ring period of 3.68 μs. The timing synchronization consisted of two parts: the sweeping circuit and the gating circuit. In order to minimize the synchronization jitter, the sweeping pulse was implemented at constant frequency (1 kHz), which was chosen to be 1/272 of the P0 frequency. The signal was fed into the external trigger input of a delay generator (SRS-1) after the frequency divider. The output pulses from SRS-1 were used to trigger the sweeping circuit, so that the synchronization between the sweeping pulses and the x-ray pulses can be implemented by varying the delay time of SRS-1. The signal from the frequency divider was also fed into another delay generator (SRS-2) and the output was used to trigger the gating circuit of the MCP. There are two functions for the SRS-2: the first is to synchronize the gating pulses and the x-ray pulses by varying the delay time of its output channel A, the second is to divide the gate frequency by varying the delay time of its output channel C. As a result, the operation frequency of the gating pulses can be from 1 kHz to 0.1 Hz.

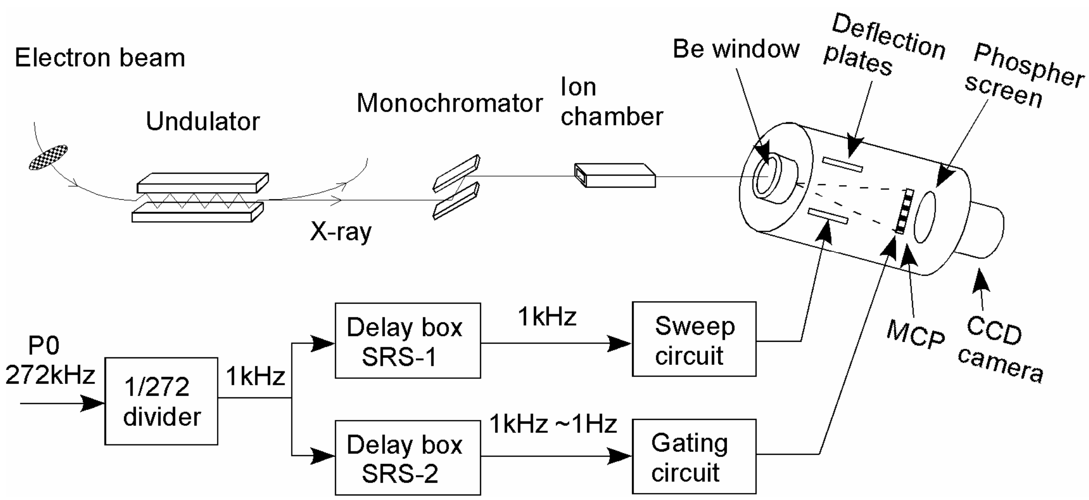

Figure 1. Diagram of the experiment setup.

Because the streak camera was operated in a much lower repetition rate than the x-ray pulses from the APS storage ring (6.7 MHz at the 24-bunch standard operating mode), only an extremely small fraction of the x-ray pulses contributed to the recorded signal in the streak camera, and the vast majority contributed to the noise. In order to optimize the signal-to-noise ratio (S/N), it was necessity to gate the MCP. The gating circuit consists of four MOSFET transistors. A high-voltage power supply (-2.5 kV) was connected to a number of string transistors through a 2 kΩ resistor. The MOSFET transistors were triggered separately by a shaping amplifier. The output pulse with a pulse width of 20 ns (FWHM) and an amplitude of –2 kV was fed into the MCP input. Due to the meander-type deflection plates, the design of the sweeping circuit was eased by the fact that the deflection sensitivity of our streak tube was as high as 20 cm/kV.[7] Only a 100-V bias was needed to sweep electrons across a 20-mm-diameter phosphor screen. The sweeping circuit consisted of three avalanche transistors. A high-voltage power supply (+850 V) was connected to the string transistors through a 1 MΩ resistor. In order to achieve a better stability, the static current in the string was around 50 μA and the trigger pulse was shaped to fast rise time and higher voltage amplitude by using another avalanche transistor. The output sweeping pulse with a rise time of 2 ns and an amplitude of 400 V was directly fed into one arm of the deflection plates. The other arm of the deflections was connected to a bias power supply (+200 V).

The most important characteristics of the photocathode was its sensitivity. The CsI photocathode used in this streak camera was provided by Luxel, Ltd. It consisted of a Lexan substrate with a thickness of 1018 Å, which was coated

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with 254 Å aluminum and then 1585 Å CsI. The vertical slit height of the anode was set to 10 μm. The horizontal width was 3 mm. The relative sensitivity of this photocathode was measured using a monochromatic x-ray beam in the energy range of 6 – 21 keV, as shown in Fig. 2. The streak camera was operated in sweeping mode at a repetition rate of 1 kHz.

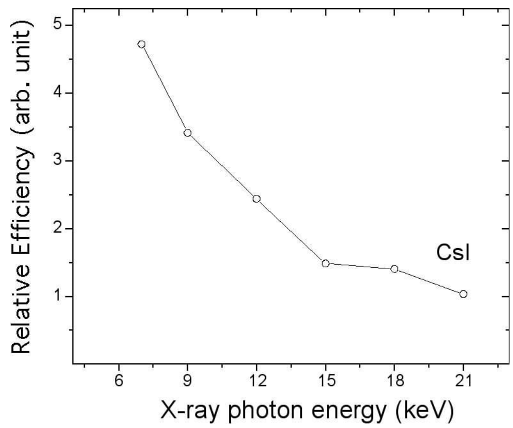

Figure 2. Relative sensitivity of the CsI photocathode in the x-ray photon energy range from 7 to 21 keV.

Figure 3 shows the result of a single-shot measurement of the x-ray pulse recorded by the streak camera with a full sweep range of 1.5 ns across the CCD. The x-ray energy was 8.0 keV with a beam intensity of 1.6×10^{12} ph/s. The vertical and horizontal axes in Fig. 3a correspond to space and time, respectively. The repetition rate of the gating pulse was 1 Hz. The exposure time of the CCD camera (thermoelectric cooled, 1024×1024 pixels) was set to 1 s. The sweeping nonlinearity was calibrated to be less than 5%. The measured pulse width was 120 ps (FWHM). The small peaks (A and B) in Fig. 3a were due to the electrons produced by x-rays hitting the wall of the streak tube.

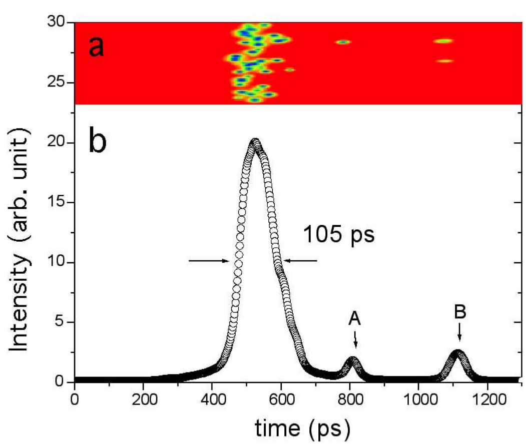

Figure 3. Single-shot measurement of the single x-ray pulse: a) Image of the single pulse collected by the CCD camera; b) Averaged lineout of the single-shot streak image.

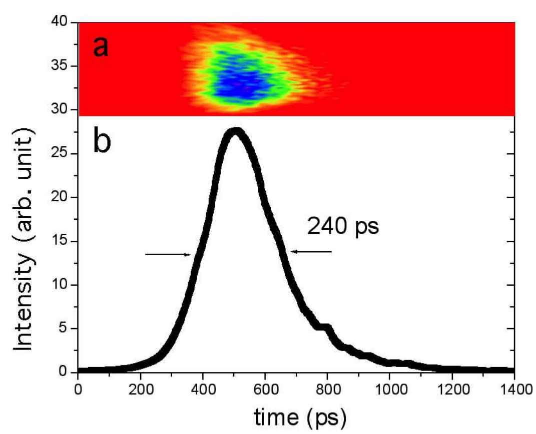

Figure 4. Accumulative measurement of 1000 x-ray single pulses: a) Integrated streak image collected by the CCD camera; b) Averaged lineout of the accumulated streak image.

Figure 4 shows the accumulative measurement of 1000 shots while the repetition rate of the gating pulse was 1 kHz and the exposure time of the CCD camera was also set to 1 s. The pulse width (FWHM) was 240 ps. This was due to

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the timing jitter of the electronic sweeping pulses, mainly contributed by the frequency divider circuit, the delay box and sweeping pulse. The electronic mean-square timing jitter (Δt^2_{jitter}) can be calculated by

$$\Delta t^2_{jitter} = \Delta t^2_{meas} - \Delta t^2_{ss}, \quad (1)$$

where Δt_{meas} is the measured pulse width in the accumulation mode (estimated to be 240 ps), Δt_{ss} the single-shot pulse width (estimated to be 105 ps, see Figure 3b). Therefore, the electronic timing jitter is calculated to be 215 ps. The slow decay of the falling edge in Fig. 4b may also be caused by the electrons produced by x-rays hitting the wall of the streak tube.

III. DISCUSSION

Since a single bunch of the x-ray pulses can be measured with the streak camera, it is possible to perform statistical analysis on several characteristic quantities, such as the x-ray pulse width, measured intensity fluctuation and the electronic timing jitter of the sweeping pulses. At 8 keV, the flux measured by the ion chamber in front of the streak camera was 1.6×10^{12} ph/s for the full beam. The number of single x-ray bunch photons is calculated to be 2.4×10^5 ph/pulse. Due to the large beam size and the small slit width (10 μm) of the anode, only about 1000 photons can go through the slit. If the quantum efficiency of the CsI photocathode is less than 5%, the number of photoelectrons produced by single bunch would be less than 50, therefore, all the measurement results are dominated by the statistical fluctuation (> 15%). Here, we can use the 100-single-shot measurement of the x-ray single bunch to obtain the statistical analysis on the beam properties, as well as the characteristics of the electronic-trigger circuit.

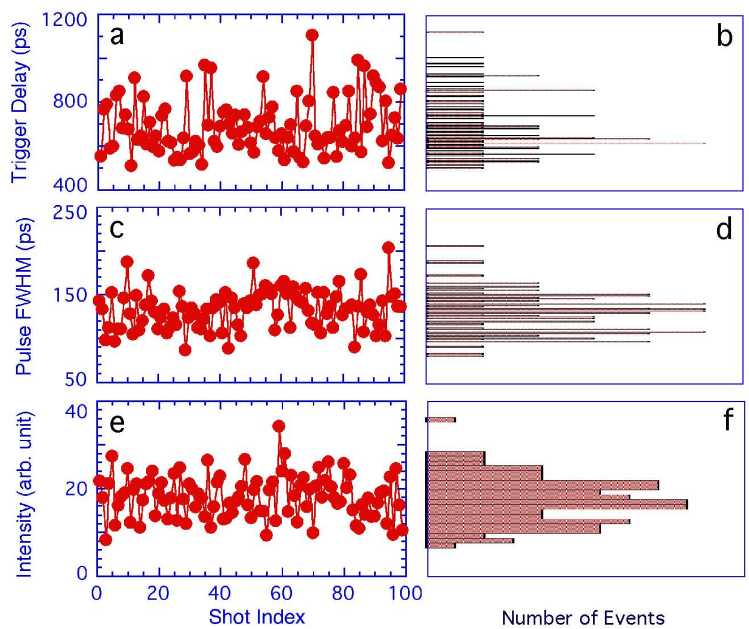

Fig. 5. Statistics of the single-shot single-bunch measurement of the x-ray pulses: a), c) and e): trigger delay, pulse width (FWHM) and single-pulse photon intensity, respectively, and, b), d) and f): their corresponding histograms.

In Figs. 5a and 5b, the trigger delay values and the histogram are displayed showing that the jitter in the delay is about 230 ps. This value is consistent with the value obtained from the accumulated pulse width shown Fig. 4b. We note that the distribution of the delay is not symmetrically distributed, which may also contribute to the long falling edge of accumulated streak camera response (Fig. 4b). Noted that, in an actual operating mode, the streak camera would

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be triggered by a fs-laser pulse generated by an ultrafast photoconductive switch. The synchronization jitter will be dominated by the jitter in the storage ring trigger signal, which ranges from 1 to 10 ps, much less than what is encountered in this experiment. The single-shot x-ray pulse width (FWHM) was also measured and is shown in Fig. 5c with its histogram (Fig. 5d). The pulse width fluctuated from 90 to 200 ps. The mean value is at 120 ps with the APS standard 24-bunch singlet fill patterns, which is consistent with the values previously measured using visible light streak cameras that detect the visible light component of the synchrotron radiation. The most important piece of information is from the measurement of the measured single-bunch x-ray intensity fluctuation shown in Fig. 5e. The fluctuation of the measurement result reveals the number of registered photons is between 20 and 30 in each shot, given that the fluctuation is at a level of 20%. In fact, the gain of the MCP and the sensitivity of the CCD are high enough for detecting a single electron from the photocathode/anode slit. Each of the bright spots in Fig. 3a corresponds to one photoelectron. The total number of electrons detected can be directly read out by counting the spots in the image. From this measurement, one can speculate that the single-shot experiment would be well possible if the entire beam can be focused to pass through the 10-µm aperture of the anode. Also, combined with a wide bandpass x-ray beam, the streak camera can detect the number of photons per bunch, at a level more than 4 orders of magnitude higher than what was measured in this study. Therefore, it will be sufficient to perform single-shot experiments using the streak camera to study ultrafast and irreversible phenomena that also only require low detection dynamics range.

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