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An accumulative x-ray streak camera with sub-600-fs temporal resolution and 50-fs timing jitter

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We demonstrated that the shot-to-shot timing jitter of an x-ray streak camera was reduced to close to 50 fs when it was triggered by a standard kilohertz laser with 1.2% rms pulse energy fluctuation. This was achieved by improving the response time of deflection plates and the rise time of the ramp pulse generated by a photoconductive switch, and by operating the photoconductive switch at optimum conditions. Furthermore, after reducing the angular distribution of electron bunch, the temporal resolution of the x-ray streak camera operating in accumulation mode was measured to be better than 600 fs. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1577213]

Ultrafast, time-resolved x-ray scattering and spectroscopy measurements have proven powerful for studying structural and electronic dynamics during laser–matter interactions on picosecond and subpicosecond time scales.[1] The methods used most fall into the laser-pump and x-ray-probe category. Although the development of ultrafast lasers advanced rapidly, the paucity of ultrafast x-ray detectors in the same temporal range has seriously limited the application of x-ray measurements as a structural probe to elucidate highly transient phenomena. Only with x-ray streak cameras, whose temporal resolution can potentially be improved to hundreds of femtoseconds, has it become possible to employ relatively long x-ray pulses (50–100 ps) from synchrotron radiation sources.[2–4] In these experiments, kilohertz Ti:sapphire lasers were used to pump the samples and to trigger the photoconductive switches of the streak cameras. Due to the relatively low instantaneous x-ray intensity and the low dynamic range of the streak cameras, accumulation over thousands of x-ray (and laser) shots is of absolute necessity. Incident laser-pulse energy affects the switch resistance and the charges created, thereby, introducing timing jitters in the triggering circuit. Therefore, the temporal resolution of a streak camera is normally limited by the laser-pulse energy fluctuation, which is 1%–2% rms for a typical kilohertz laser.

Currently, there are two methods to reduce the synchronization jitter. First, by reducing the laser energy fluctuation to 0.5%, Naylor *et al.*, showed that the timing jitter can be significantly reduced.[5] However, this approach seriously limited the portability of the x-ray streak camera for synchrotron applications. Second, by employing multiple photoconductive switches to compensate the laser fluctuations, others showed that 0.8-ps time resolution can be achieved.[6] Although having many advantages, the more complicated photoelectronic circuitry and requirement of more laser power to trigger the switches may limit the application of this method. In this letter, we report that the timing jitter of a classic streak camera can be reduced to 50 fs, even triggered by a laser with 1.2% rms fluctuation, while retaining the simple structure of the camera with a single fast switch. Therefore, the time resolution of the accumulation streak camera is only determined by the intrinsic or the so-called single-shot resolution, which has a theoretical limit of ~200 fs in the hard x-ray regime.[7]

The x-ray streak camera, schematically shown in Fig. 1, is based on a classical camera with significant modifications and improvements of every component, given that the original device had a time resolution of about 2 ps.[7–9] In the streak tube, the photoelectrons produced by the x-ray-sensitive photocathode are accelerated by a higher field (15 kV/mm) between the photocathode and the anode. The photoelectrons are focused by a set of quadrupole electrostatic lens placed immediately before they enter the field between a pair of meander-type deflection plates. The plates are driven by high ramping voltage pulses generated in a single photoconductive switch circuit. Finally, the electrons are imaged on the microchannel plate/phosphor screen, and the streak images are accumulated in a CCD chip coupled to the phosphor screen with a photographic lens.

The timing jitter caused by the laser-pulse energy fluctuation can be evaluated analytically. When a femtosecond laser pulse impinges on a photoconductive switch, the resis-

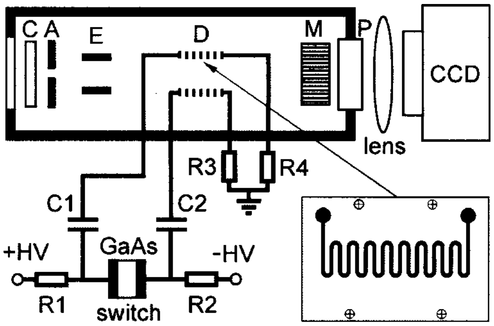

FIG. 1. Schematic of the x-ray streak camera. C: photocathode; A: anode; E: electrostatic lens; D: meander-type deflection plate; M: microchannel plate; P: phosphor screen; C_1, C_2: DC blocks; R1, R2: 1-MΩ resistors; R3, R4: 50-Ω matching resistors; ±HV: high voltage bias.

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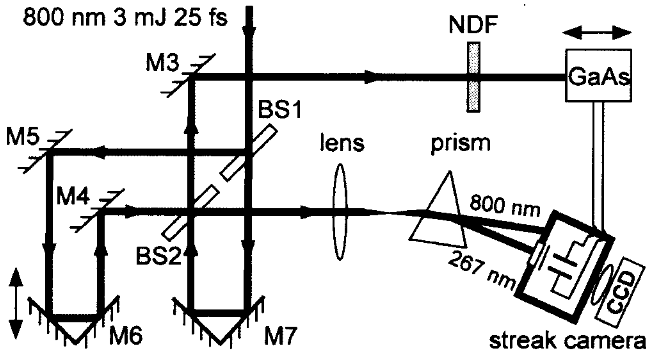

FIG. 2. Schematic of the streak camera testing setup. BS1, BS2: 50% beam splitters; M3, M4, M5, M6, M7: 100% reflection mirrors; NDF: neutral density filter; lens: focal length $f = 100$ mm; GaAs: photoconductive switch. The GaAs switch and M6 are mounted on two separate translation stages so that the optical delays can be adjusted with micrometer resolution.

tance of the switch is inversely proportional to the absorbed laser energy E_a, and is given by[10] $R_s = h\nu l V_0/2v_s e E_a = \alpha/E_L$, where h is Planck's constant, ν the optical frequency, l the gap width between two electrodes, V_0 the voltage across the switch, v_s the carrier saturation velocity, e the charge of an electron, α the so-called sensitivity coefficient, and E_L the incident laser energy in μJ. The improved switch, made from semi-insulate GaAs (10^7 Ω cm) with two deposited copper electrodes 2 mm apart, is mounted on a 50-Ω microstrip line. The output of modified meander deflection plates is terminated by a long 50-Ω transmission line as well. Therefore, the output impedance of the equivalent circuit is 50 Ω. These parameters yield $\alpha = 25$ Ω μJ. Since the relative time fluctuation is equal to that of the voltage amplitude,[11] the timing jitter caused by the fluctuation of sweeping pulse amplitude can be written as

$$\tau_j = t_{\text{ramp}} \cdot \frac{\Delta E_L}{E_L} \cdot \frac{\alpha}{\alpha + R \cdot E_L}, \tag{1}$$

where t_{ramp} is the combined rise time of the switch-generated ramping pulse and the deflection plates, which was reduced to 150 ps in the present circuit,[12] and $\Delta E_L/E_L$ is the shot-to-shot laser energy fluctuation. The design of our photoconductive switch is eased by the high deflection sensitivity (20 cm/kV) of the streak tube. Only a ±50-V bias is needed to sweep electrons across a 20-mm-diameter phosphor screen. The reduction of the rise time marks the most significant improvement of the device.

The timing jitter was evaluated experimentally by measuring the delay time of a photoconductive switch as a function of laser-pulse energy as follows. The trigger delay t was determined from the relative shifting of the streak strip with varying incident laser energies E_L, at a fixed path-length delay. The measurement was performed using the newly established high-intensity laser facility, Kansas Light Source, at Kansas State University, where the shot-to-shot laser-pulse energy variation is measured to be 1.2% rms. Since the photocathode of the x-ray streak camera is also sensitive to UV light, the third harmonic (267 nm) of the laser pulses was used to test the camera with a setup that is schematically shown in Fig. 2. A Mach–Zehnder interferometer was used to split the primary laser beam into two beams containing identical pulses per shot with known time delay controlled by their optical path difference. One of the beams was attenuated with a variable neutral density filter to vary the laser energy impinging on the GaAs photoconductive switch. The other beam was used to produce third-harmonic UV pulses by focusing it in air with an $f = 100$-mm lens. A prism separated the UV beams from the original 800-nm beams. The UV pulses illuminated the photocathode of the camera with adjustable time delay. The streak images of the UV pulses were integrated by a CCD camera (thermoelectric-cooled, 1024×1024 pixels) with an integration time of 6 s (6000 shots at 1 kHz). The measured t versus E_L curve is shown Fig. 3(a). When $E_L < 70$ μJ, the timing jitter τ_j due to rms laser energy fluctuation σ, can be evaluated from the direct derivative of the curve as $\tau_j = |k| E_L \sigma$, where $|k|$ is the absolute value of slope of the t versus E_L curve. Thus, determined jitter varies around 110 fs (±28 fs), as shown in the inset to Fig. 3(a). Due to instrumental noise at higher laser power ($E_L > 70$ μJ), the slope of the curve and the jitter, shown in Fig. 3(b) can only be calculated from the analytical derivation of a function best fitted to the t versus E_L curve. The simplest function is found to be a third-order polynomial, shown as the solid line in the inset to Fig. 3(b). The jitter decreases from 110 to about 50 fs as the laser energy increases to 150 μJ. At this energy, we did not observe any damage to the photoconductive switch. Such a small jitter was the result of the extremely fast response time from the combination of the improved switch/deflection plates.

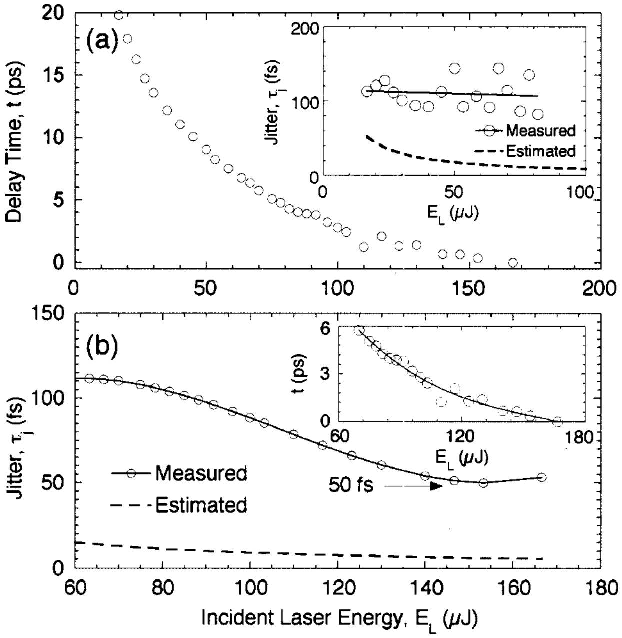

FIG. 3. Measured trigger delay and jitter of the photoconductive switch as a function of incident laser energy: (a) trigger delay, and (b) jitter at high incident laser energies and theoretical estimate of jitter in this energy range. The inset to (a) depicts the measured jitter at lower incident laser energies (open circles) with a linear fit (line) and theoretical estimate of the jitter (dashed line). The inset to (b) illustrates a third-order polynomial (line) fit to the delay data taken at higher incident laser energies (open circles).

The calculated jitter evaluated by the simple theoretical calculation [illustrated in Eq. (1)] with $\Delta E_L/E_L$ of 1.2%, is also shown in the inset to Fig. 3(a) and in Fig. 3(b). Although the discrepancy between the measured jitter and the theoretical estimate is apparent, the values are within the same order of magnitude in tens of femtoseconds. The calculation did

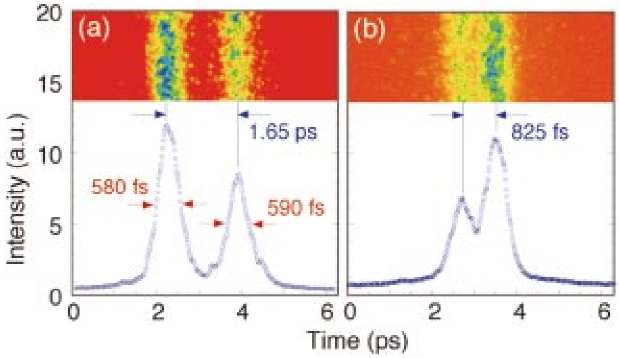

FIG. 4. (Color) Averaged lineout of the streak images with corresponding actual images (top) of two 30-fs UV pulses separated by (a) 1650 fs and (b) 825 fs.

not account for other factors, including prepulses and amplified spontaneous emission from the laser that may well introduce additional jitter. Parenthetically, we should also note that the 50-fs jitter is probably the low detection limit of the streak camera due to its finite temporal resolution on the order of hundreds of femtoseconds. Since many current femtosecond kilohertz lasers produce $1\sim2$-mJ pulses, and one prefers to use most of the energy for pumping the samples, the amount of energy available for triggering the photoconductive switch is limited. Nevertheless, even with 20 μJ, the jitter is close to 110 fs. Compared to a streak camera using multiple switches,[6] the present single-switch design requires much less laser energy to trigger. We would also like to emphasize here that the sub-100-fs jitter is achieved with a laser that has fluctuation (1.2% rms) similar to that of commercial femtosecond lasers; therefore, it is easier to implement than to improve the laser stability.[5]

With such a low triggering jitter, the temporal resolution of a streak camera operating in accumulation mode is no longer limited by the laser intensity fluctuation. The main factor that limits the temporal resolution is the transit-time dispersion of the photoelectrons as they travel from the photocathode to the deflection plates.[7,9,12] One solution to improve the resolution is to increase the field strength between the photocathode and anode. To avoid electric discharge and the lens effect, the electric field was kept at a moderate level (15 kV/mm). The other limiting factor is the sweeping aberrations of the deflection plates, which are significant for photoelectrons with large beam divergence. The divergence can be reduced by collimation with a pair of slits. To preserve the photoelectron signal intensity, electrostatic lenses were also an effective way to collimate the photoelectrons. All these measures resulted in a much improved time resolution, shown clearly in the lineout of the streak image accumulated with the 6000 UV shots (Fig. 4). After proper calibration, 30-fs UV pulses were recorded by the streak camera as 590-fs-wide (full width at half-maximum) streak strips. In the two cases shown, the delays between the two UV pulses were set to 1650 and 825 fs, corresponding to a 500- and 250-μm optical path difference, respectively. It is worth noting that, with the meander-type sweeping plate, the achievable sweep rate is 15 fs/pixel on a CCD. Since the third-harmonic UV pulse duration is at least one order of magnitude shorter than 590 fs, the measured streak width is unambiguously the time resolution of the streak camera in the accumulation mode.

In conclusion, we have demonstrated experimentally an accumulative x-ray streak camera with better than 600-fs time resolution and sub-100-fs, even 50-fs, timing jitter due to intensity fluctuation in the triggering laser. The timing jitter becomes irrelevant to the temporal resolution of the streak camera. To further reach its intrinsic temporal resolution limit, the only methods are to reduce the deflection aberration and electron transit-time dispersion. When a streak camera can be operated reliably in the sub-picosecond regime, it will not only make a significant impact on ultrafast science using third-generation synchrotron x-ray sources, but will also play an important role in timing diagnosis for experiments to be carried out at fourth-generation x-ray sources, in which detecting sub-picosecond time delays is essential.

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