

Multishot Accumulation X-ray Streak Camera with Subpicosecond Temporal Resolution

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Introduction

During the last few years, x-ray streak cameras have been used at synchrotron facilities to study structural changes in solids in the ultrashort time domain [1]. In these experiments, femtosecond, kilohertz, Ti:sapphire lasers are used to pump the samples and to trigger the photoconductive switches of the streak cameras. Because of the relatively low instantaneous x-ray signal level, accumulation over thousands of x-ray (and laser) shots is required. When a streak camera operates in the accumulation mode, its temporal resolution is normally limited by the timing jitter caused by the shot-to-shot pulse energy fluctuation of the lasers, which is $\sim 1\text{-}2\%$ root-mean-square (rms) for a typical kilohertz laser. The timing jitter has been reduced to subpicosecond levels by improving the laser stability down to the $\sim 0.5\%$ rms level [2]. To reduce the jitter even further, extra GaAs switches can be added to compensate the sweep pulse amplitude variation resulting from laser intensity fluctuation [3]. We demonstrated that the timing jitter can be reduced to the 30-fs level with just one switch triggered by a standard kilohertz laser with $\sim 1.2\%$ rms fluctuation. The resolution is further improved by restricting the transverse electron angular distribution.

Methods and Materials

The configuration of the new x-ray streak camera is shown schematically in Fig. 1. In the streak tube, the x-ray-produced electrons from the photocathode are accelerated by the high field (15 kV/mm) between the photocathode and the anode. The electrons then enter the region between a pair of deflection plates. The electrostatic lens is used as a focal lens. The deflection plates are driven by a pair of ramp voltages produced by a single photoconductive switch. Finally, the electrons are imaged on the microchannel plate/phosphor screen, and the signals are accumulated onto a charge-coupled device (CCD) camera.

The design of our photoconductive switch is eased by the fact that the deflection sensitivity of our streak tube is very high (20 cm/kV). Only ± 50 V are needed to sweep electrons across a 20-mm-diameter phosphor screen [4]. The switch was made from semi-insulate GaAs with a resistance of $107 \Omega\text{-cm}$. The active area of GaAs is about 0.2 cm^2 . To reduce the contact resistance,

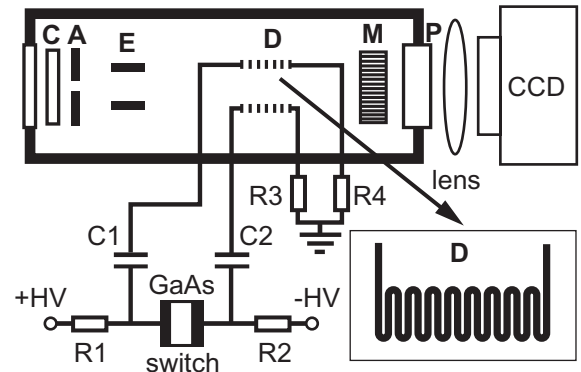


FIG. 1. Schematic of x-ray streak camera. *C* = photocathode, *A* = anode, *E* = electrostatic lens, *D* = meander-type deflection plate, *M* = microchannel plate, *P* = phosphor screen, *C1* and *C2* = DC blocks, *R1* and *R2* = $1 \text{ M}\Omega$ resistors, *R3* and *R4* = 50Ω matching resistors, and *+HV* and *-HV* = high-voltage bias.

two copper electrodes were deposited on the switch with a gap of 2 mm between them. In order to get a fast response time, the switch was mounted on a circuit board with a 50Ω microstrip line.

Results

The timing jitter was evaluated experimentally by measuring the delay time of a photoconductive switch as a function of laser-pulse energy. We first measured the trigger delay as a function of laser energy by using the streak camera. Then, from this result, one can deduct the timing jitter as a function of laser energy.

This experiment was performed by using the newly established high-intensity laser facility, Kansas Light Source, at Kansas State University. Since the x-ray streak camera is also sensitive to ultraviolet (uv) light, we used the third harmonic of the laser pulses to test the camera. The system setup is shown in Fig. 2.

The Kansas Light Source produces 3-mJ, 25-fs pulses at a repetition rate of 1 kHz. The shot-to-shot pulse energy stability is 1.2% rms evaluated by a Tektronix TDS784D oscilloscope. A Mach-Zehnder interferometer was used to produce two laser beams. Each beam contains two identical laser pulses per shot, with the known time delay calculated from the optical

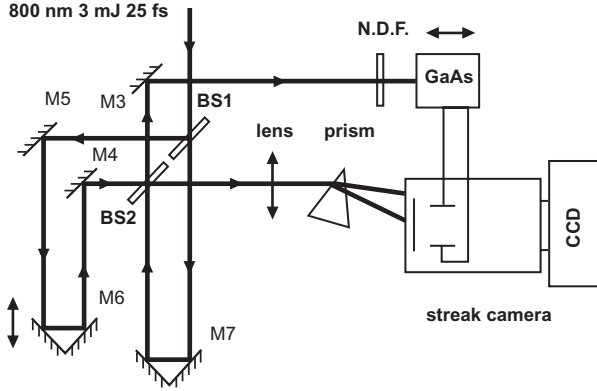


FIG. 2. Measurement system setup. BS1 and BS2 = 50% beam splitters; for M3, M4, M5, M6, and M7, R = 100% mirror; N.D.F. = neutral density filter; for lens, $f = 100$ mm; GaAs = photoconductive switch.

path length difference of the two paths. One of the beams was used to produce the third-harmonic pulses of a Ti:sapphire laser by focusing the two laser pulses in air with a lens in which $f = 100$ mm. A prism was used to separate the uv beam from the infrared (ir) beam. The uv light illuminates the photocathode of the camera. The other beam is attenuated with a variable neutral-density filter to control the laser energy for triggering the photoconductive switch. The streak images were integrated by a thermoelectric (TE)-cooled Photometrics CCD camera (1024×1024 pixels). In order to obtain a long time window on the phosphor screen of the streak camera, the streak camera was operated at a relatively low sweep speed with 45 fs/pixel on CCD. The streak images were accumulated on the CCD camera with an integration time of 6 seconds. Fig. 3 shows the measurement result of relative delay as a function of laser energy. The sweep nonlinearity is taken into account, which is shown as a inset in Fig. 3.

The measured time delay versus laser energy can be fit nicely with an exponential function:

$$t = 19.199 \exp\left(-\frac{E_L (\text{ J}) - 16.667}{43.079}\right).$$

The timing jitter can be expressed by

$$\tau_j = |k| E_L \sigma, \quad (1)$$

where $|k|$ is the absolute value of slope in Fig. 3, E_L is the laser energy, and σ is the laser energy stability.

The jitter deduced from Fig. 3 by using Eq. (1) is shown as Fig. 4. The jitter of the switch is reduced to about 30 fs at 160 μJ of laser energy; at this energy, we did not observe any damage to the photoconductive switch. Fig. 5 shows the lineout of the streak image accumulated with the 6000 shots. The sweep speed is

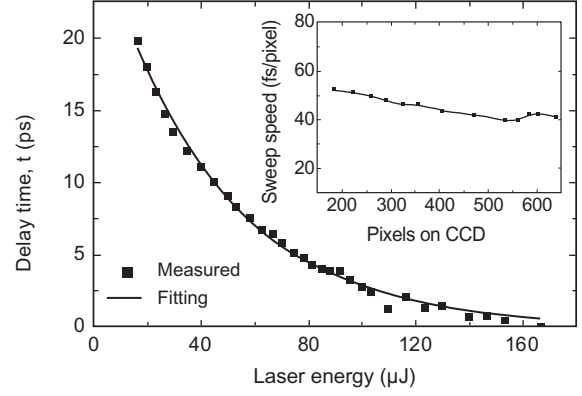


FIG. 3. Measured trigger delay of the photoconductive switch as a function of laser energy. The inset is measured result of sweep nonlinearity

15 fs/pixel on CCD. The full width at half-maximum (FWHM) of the measured pulse width is 590 fs, while the interval time between the two pulses is 1.65 ps.

Discussion

The main factor that limits the time resolution of the streak camera in single-shot mode is the transit-time dispersion of the photoelectrons as they travel from the photocathode to the deflection plates. It was calculated previously to be 276 fs, which can be improved by increasing the field strength between the photocathode and anode [5]. The other factors are aberrations of the deflection plates due to sweeping. We found that the effect of aberrations is significant for photoelectrons with a large initial angle. It was reduced by blocking electrons with a large initial angle.

The results also show that there is a tradeoff between the pulse energy and the jitter. Since many commercial femtosecond kilohertz lasers produce 1 to ~ 2 -mJ pulses, and it is preferred that most of it be used for

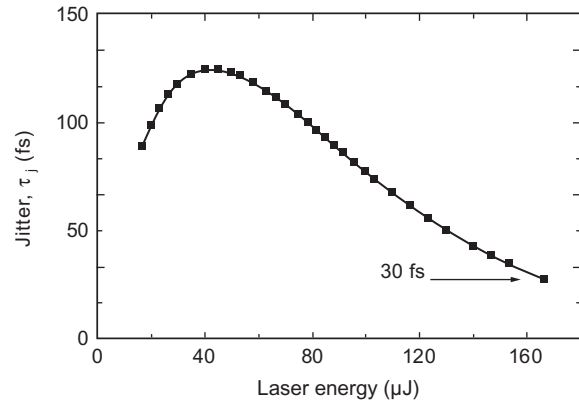


FIG. 4. Jitter as a function of laser energy for laser stability $\sigma = 1.2\%$ derived from the delay measurement in Fig. 3.

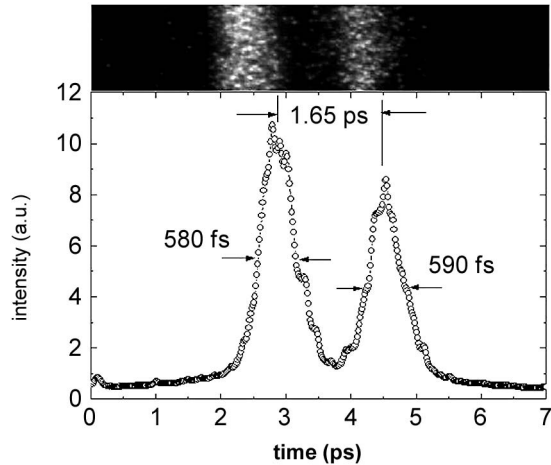


FIG. 5. Averaged lineout of the streak images with corresponding actual images (top) of two 30-fs uv pulses separated by 1.65 ps

pumping the samples, the amount of energy available for triggering the photoconductive switch is limited. Nevertheless, even with 20 μ J, the jitter is less than 130 fs.

Acknowledgments

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