Development of a laser-triggered ultrafast streak camera for time-resolved x-ray diffraction

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ABSTRACT

The advent of CPA femtosecond lasers has opened the way to a new regime of interaction with atoms and molecules. In some experiments like time-resolved x-ray diffraction of laser-excited samples, the signal to be measured can contain very few photons and repetition rates up to 1 kHz are required. The laser-triggered x-ray streak camera system is therefore a promising tool for the study ultrashort x-ray events. We present the results of the characterization tests performed on our subpicosecond x-ray streak camera at the University of Michigan and at the European Synchrotron Radiation Facility. This new ultrafast diagnostic is triggered by a short laser pulse and can acquire images at rates up to 1 kHz and features a subpicosecond time resolution along with a 40 μm spatial resolution. We discuss the different issues related to the interaction between the laser pulse and photo-conductive switches, the synchronization of the detector.

Keywords: x-ray detectors, streak cameras, ultrafast-diagnostics, ultrashort lasers

1. INTRODUCTION

The generation of ultrashort x-ray pulses has become of great interest to probe femtosecond time-scale processes in many fields such as biology and molecular chemistry. Up to now, many measurement techniques involve third generation synchrotron light sources. These synchrotrons are the most powerful source of hard x-rays. However, it is generally accepted that the actual synchrotron technology does not allow x-ray pulse length to be shorter than 50 ps. Some recent techniques involve x-ray pulse shaping using a crystal irradiated by a laser pulse. This can give a resolution of about 2 ps.

To overcome the temporal resolution limitation, another concept was recently proposed. The method consists of sending a femtosecond laser pulse on the sample while it is irradiated by a long high brilliance x-ray pulse. The diffraction pattern is then analyzed by a subpicosecond x-ray streak camera. Since the perturbation induced by the laser pulse is expected to be of small amplitude, this experiment has to be repeated thousands of times in order to get a measurement with suitable dynamic range. To accumulate such a number of images, the streak camera has to be perfectly synchronized with the laser pulses. This technique requires state-of-the-art technologies from three different field of expertise: the synchrotrons, the femtosecond CPA lasers as well as the ultrafast detectors.

We present some of the results of the characterization tests performed on our subpicosecond x-ray streak camera at INRS, at the University of Michigan and at the European Synchrotron Radiation Facility. This new ultrafast diagnostic is triggered by a short laser pulse and can acquire images at rates up to 1 kHz and features a subpicosecond time resolution along with a 40 μm spatial resolution. We discuss the different issues related to the streak camera, the synchronization with the laser and the performance of the whole system.

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2. THE SUBPICOSECOND X-RAY STREAK CAMERA

A new streak camera was recently developed at the Institut National de la Recherche Scientifique (University of Québec)\(^3\). This x-ray camera was designed for use with a wide photocathode (15 mm) and features a unique combination of 500 fs single-shot resolution together with a 40 μm spatial resolution at the photocathode. This remarkable performance is achieved with a radically new design and an innovative bilamellar electron tube built by Photonis (formerly Philips Photonics) in which temporal and spatial resolutions can be independently adjusted.

Figure 1 shows a lineout of a streak trace obtained in a single shot with the INRS PX1 x-ray streak camera. The 2 keV x-rays were produced with the INRS laser-plasma ultrashort x-ray source. The duration of the x-ray pulse was measured with a cross-correlation technique\(^4\) and is about 500 fs. The measured signal has a FWHM of 700 fs and is a convolution on the source and the instrumental resolution. Assuming that this convolution is quadratic, the single-shot time resolution of the x-ray streak camera is about 500 fs.

The spatial resolution of 40μm (with 80% contrast) is conserved on 1.5 cm along the entrance slit, even in sweeping mode\(^5\).

3. TRIGGERING WITH A SHORT LASER PULSE

In x-ray diffraction experiments, the number of x-ray photons is so low that it is difficult or even impossible to obtain a time-resolved measurement in a single sweep of a streak camera. It is therefore necessary to accumulate several sweeps on the same streaked image. The ability to average will provide adequate signal-to-noise ratios when working with very low light intensities. Averaging the light pulses on a subpicosecond streak camera requires a perfect synchronization between the light pulses to analyze and the sweeping of the photoelectron bunch in the streak tube. The systems working in synchroscan mode can only achieve a synchronization jitter of a few picoseconds.

The solution described in this work consists of using an ultrafast x-ray streak camera and generating its sweep ramps with photoconductive switches\(^6\) that are triggered by a short laser pulse. Before sweeping, high voltage is applied on the GaAs switches. Carriers are created when the laser light is absorbed in the material and two voltage ramps of opposite sign are created and sent to the sweep plates. In principle, the synchronization of the streak camera is perfect.

In reality, the pulses produced by the laser system have an intensity profile which varies in time. Typically, the shot-to-shot amplitude stability of kHz ultrashort-pulse laser systems is a few percent. These fluctuations, give rise to an amplitude variation of the voltage ramps applied on the sweep plates which results in a time jitter on the streak camera screen.

Also, CPA femtosecond laser systems produce a low-intensity pedestal which comes a few nanoseconds before the main pulse. This pedestal is mostly created in the amplification stages and comes from ASE (amplification of spontaneous emission). For kHz lasers, the intensity of the pedestal is usually 3 orders of magnitude smaller than the peak intensity. This is however enough to increase the conductivity of the switches and charge the sweep plates before the arrival of the main laser pulse. The fluctuations of the total energy contained in the pedestal also introduces jitter.

A previous experiment\(^7\) conducted at the University of Michigan showed the possibility of averaging many shots (up to 50) at 10Hz with an x-ray streak camera and obtaining a total time resolution of 8 ps. Some improvements\(^8\) on the streak camera, the design of the photoconductive switches and associated electronics, brought the resolution down to 4 ps. To take advantage of the subpicosecond streak camera, one needs to synchronize it within hundreds of femtoseconds.
3.1 Effect of Amplitude Fluctuations of Laser Pulses

When a femtosecond laser pulse interacts with the photoconductive switch, it creates carriers in the semiconductor and the conduction is almost instantaneous. The resistivity ($R_s$) of the switches is proportional to the laser energy ($E_L$) deposited in the gap between the electrodes and is given by:

$$R_s = \frac{h v l V_{\text{applied}}}{2 v_s e E_{\text{abs}}}$$

where $h$ is Planck's constant, $v$ is the optical frequency, $l$ gap width, $V_{\text{applied}}$ is the bias voltage, $v_s$ is the carrier saturation velocity, $e$ is the charge of the electron and $E_{\text{abs}}$ is the laser energy absorbed. For convenience, we regrouped all constants in one which we call the sensitivity coefficient ($\alpha$). This coefficient includes the absorption coefficient of the switch material so that we can express the equation in terms of incident laser energy ($E_L$):

$$R_s(\Omega) = \frac{\alpha}{E_L(\mu J)}$$

For classical Auston switches as used in previous experiments, the sensitivity coefficient was $\alpha \approx 8000 \, \Omega \cdot \mu J$. Thus 800 $\mu J$ were needed to reach a resistivity of 10 $\Omega$. Typically, the new switches that were used for this work have a sensitivity of $\alpha = 25 \, \Omega \cdot \mu J$. Now, only 2.5 $\mu J$ are required to bring the switch to a resistivity of 10 $\Omega$. This major improvement opens the way to experiments where low-energy lasers are used. For example, a typical kHz laser system can deliver about 1 mJ per pulse such that only a few percent of the available laser energy is used to trigger the streak camera.

In our setup, the switches are mounted on a 50$\Omega$ impedance line and the plates are an open circuit. The asymptotic value of the voltage on each sweep plate is then given by:

$$V_{\text{max}}(V) = 2 V_{\text{applied}} \frac{50\Omega}{R_s + 100\Omega} = 2 V_{\text{applied}} \frac{50\Omega \cdot E_L(\mu J)}{\alpha + 100\Omega \cdot E_L(\mu J)}$$

where $V_{\text{applied}}$ is the voltage applied on the switch before the interaction with the laser. If from shot to shot, the laser energy fluctuates of a certain value ($\Delta E_L$), the amplitude of voltage will fluctuate as follows:

$$\frac{\Delta V_{\text{max}}}{V_{\text{max}}} = \frac{\Delta E_L}{E_L} \frac{\alpha}{\alpha + 100\Omega \cdot E_L(\mu J)}$$

where ($\Delta E_L/E_L$) is the shot-to-shot stability of the laser system. The time fluctuation ($\Delta t_{\text{ramp}}/t_{\text{ramp}}$) being equal to the fluctuation of the voltage ($\Delta V/V$), the contribution of peak-to-peak fluctuations to the time resolution of the system can be written as:

$$\tau_{\text{peak}} = t_{\text{ramp}} \frac{\Delta E_L}{E_L} \frac{\alpha}{\alpha + 100\Omega \cdot E_L(\mu J)}$$

where $t_{\text{ramp}}$ is the time required for the voltage to deflect the electron beam at the center of the screen. One can see that for $E_L < \alpha/100\Omega$ the jitter is constant for $E_L > \alpha/100\Omega$ the jitter decreases almost linearly as the laser energy increases. Also, $\tau_{\text{peak}}$ is proportional to the shot-to-shot stability of the laser system. As an example, using $E_L = 30 \, \mu J$, the resistance of the switch is brought to $R_s \approx 1 \, \Omega$ and taking $t_{\text{ramp}} = 500$ ps, one would expect a contribution of $\tau_{\text{peak}} = 40$ fs with a laser stability of 1%.
3.2 Effect of Laser Pedestal Fluctuations

The fluctuations of the laser pedestal bring an important contribution to the jitter. For a few nanoseconds before the main pulse, the switches are illuminated by laser light which decreases their resistivity. A small leak current passes through the semiconductor, thus charging the capacitor formed by the circuitry and the sweep plates. Just before the main laser pulse arrives, the voltage on each plate is:

\[ V_{ASE} = \frac{1}{2} \frac{V_{applied} \cdot t_{ASE} \cdot E_{L}}{c \cdot \alpha} \]

where \( t_{ASE} \) is the duration of the ASE pedestal, \( C \) is the contrast of the laser pulse and \( c \) is the capacitance of the circuit between the switch and the sweep plate. The contribution \( \tau_{ASE} \) of the pedestal fluctuations to the jitter is dictated by fluctuations of the parameters of the last term \( t_{ASE}, E_{L} \) and \( C \). They are uneasy to measure so that predicting the fluctuations of \( V_{ASE} \) is difficult.

Nevertheless, this contribution can be reduced by maximizing the contrast \( (C) \) and decreasing the peak laser energy \( (E_{L}) \). The contrast can easily be improved using solid-state or liquid saturable absorber\(^7\).

3.3 Expected time resolution

The expected instrumental resolution of the whole system can be written as the quadratic sum of all the contributions previously mentioned:

\[ \tau_{total} = \sqrt{\left(\tau_{streak}\right)^2 + \left(\tau_{peak}\right)^2 + \left(\tau_{ASE}\right)^2} \]

where \( \tau_{streak} \) is the single shot resolution of the streak camera.

We have plotted in Figure 2, the expected instrumental resolution as a function of laser energy using the typical parameters of the experimental setup used for the present work. The single-shot resolution of the streak camera is \( \tau_{streak}=500 \) fs. To compute the contribution of the shot-to-shot fluctuations of the laser \( \tau_{peak} \), we have used \( t_{amp}=500 \) ps, a laser stability \( \Delta E/E=1\% \) and a switch sensitivity of \( \alpha=25 \) \( \Omega \cdot \mu J \). Since, it is complicated to estimate the contribution of the laser pedestal we have used the form \( \tau_{ASE}=A \cdot E(\mu J) \) where \( A \) is a coefficient. We have plotted the curves for different values of \( A \) corresponding to experimental data of previous experiments on different CPA systems.

We observe that the optimal working point is obtained when the laser energy is between 5 \( \mu J \) and 100 \( \mu J \) depending on the stability of the pedestal. The figure also shows that for better ASE stability, the energy range in which the switches can be operated is wider.
4. CHARACTERIZATION OF DIAGNOSTIC

We have used the streak camera developed at INRS coupled with photoconductive switches and associated electronics. The complete system was installed at the European Synchrotron Radiation Facility (ESRF) in France.

The laser system is capable of delivering 1 mJ of 800 nm light in 150 fs pulses at a rate of 1 kHz. Most of the total laser pulse energy is available for an Optical Parametric Amplifier which is used for different experiments. About 120 μJ of laser pulse (at the 800 nm fundamental) is available for the photoconductive switches to trigger the streak camera. To perform experiments with the synchrotron x-ray pulses, the laser mode-locking is synchronized with RF frequency of the synchrotron within 10 ps.

For the purpose of the tests, we have replaced the x-ray source by the third-harmonics of the laser fundamental wavelength. As shown on Figure 3, a small fraction of the main pulse was frequency tripled using a KDP and a BBO crystal. The 267 nm light was directed on the photocathode of the streak camera. The cathode was made of palladium which is sensitive to the UV light. The images were integrated within an cooled CCD camera having a high spatial resolution (22.5 μm).

We have accumulated streaked images at a rate of 900 Hz on the CCD camera with integration times from 1 to 100 seconds. Figure 4 shows the streak trace obtained with 90,000 shots. The FWHM is 920 fs. The uncertainty comes from the measurement of the sweep speed. By quadratically subtracting the single shot resolution of 500 fs, one obtains a total jitter contribution of about 750 fs. Figure 5 shows that the width of the trace does not seem to be independent of the number of accumulated shots. This indicates that there might be a drift in the laser amplitude stability or in the ASE pedestal. Further investigation is required to explain and correct this drift.

Figure 3: Typical setup for high-repetition-rate time-resolved experiment. The HV power supply charges the switches and the short laser pulse generates the high-voltage ramp that will sweep the image across the screen of the streak camera.

Figure 4: Signal obtained on the CCD camera after an accumulation of 100 second at 0.9 kHz. The FWHM is 920 fs. The laser energy on each switch is about 60 μJ.
5. CONCLUSION

The laser-triggered streak camera system is a promising tool for the study ultrashort events in the x-ray range. The new diagnostic allows accurate time- and space-resolved measurements with an unlimited dynamic range. This device can accumulate thousands of shots at rates up to 1 kHz while conserving a subpicosecond resolution together with 40 μm spatial resolution.

The system can be used with high-repetition-rate lasers that usually have a good stability. We have shown that the jitter contributes for less than a picosecond.

This new ultrafast diagnostic opens the way to experiments that would have not been possible with the usual means, in the study of ultrafast phenomena in physics as well as in chemistry.

6. REFERENCES