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A sub-picosecond accumulating streak camera for x-rays

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Abstract
An x-ray streak camera system uses a laser triggered photo-conductive switch to synchronize the high voltage ramp applied to its sweep plates to the photo-excitation of a sample. This technique allows the jitter between successive sweeps to be kept below 100 fs compared to over 1 ps using classical methods. By accumulating a stable pulsed x-ray signal over many sweeps, a very high dynamic range can be achieved whilst maintaining a sub-picosecond time resolution. The ultimate time resolution is limited by the dispersion of electrons in the streak tube. Whilst triggering with a laser at 900 Hz we have achieved a time resolution (FWHM) of 640 fs at a detection wavelength of 267 nm for a 60 s accumulation period, corresponding to over 50 000 sweeps.

Keywords: ultrafast detector, streak camera, x-ray, synchrotron, picosecond, photoconductor, jitter synchronization, laser triggering

1. Introduction

Ultra-fast spectroscopy using femtosecond lasers is now a mature field of research. Until recently the technique has been limited to operation at wavelengths between the infrared and ultraviolet. While spectroscopy at these wavelengths can give an important insight into the dynamics of materials under the influence of ultra-fast excitation, the adoption of a pump–probe scheme with a probe wavelength in the x-ray region opens up the possibility of yielding detailed structural information of a photo-triggered reaction. Possible applications of such a laser excitation/ultra-fast x-ray probing technique range from solid state physics research to biochemistry [1–4]. Recent advances in the generation of laser-produced plasmas have allowed the production of ultra-short x-ray pulses in the picosecond range [5]. While such sources claim to be of high spectral and temporal brilliance, the very poor collimation leads to a low photon yield of the significant probe x-rays collected at the detector. Synchrotron x-ray sources of the third generation such as the ESRF (France), APS (USA) and SPRING8 (Japan) on the other hand are very intense sources of x-rays, giving a very high useful x-ray photon yield. Such high photon data collection rates are important for studying small fractional changes in the time resolved x-ray signal amplitude. Unfortunately the x-ray pulse length of such storage ring synchrotron sources operating in equilibrium is limited to the range 50–200 ps. With conventional schemes therefore, ultra-fast time resolution in the femtosecond range using a synchrotron source was not possible. Recently Mourou proposed a scheme [6–10] in which a time-resolved detector would allow sub-ps time resolution of an x-ray modulation event. The idea consisted of triggering the sweep plates of an x-ray sensitive streak tube with laser-illuminated photoconductors. This arrangement differs from conventional streak camera sweep circuits [11, 12]. Experimental use of such a device has been reported [13, 14] and for the device described here in [15]. Using this technique a 100 fs laser was used to pump a photoconductive switch and an optical parametric oscillator/amplifier, the latter in turn exciting the sample under study. This synchronization allows the perfect registering of multiple sweeps on the output screen of the streak camera (see figure 1). This idea was pursued in collaboration with the Center for Ultrafast Optical Science (CUOS, Michigan). This paper describes the work performed at the ESRF in developing this device to obtain reliable operation of the photoconductive switches, to achieve a jitter of less than 100 fs so as to improve the streak tube's time resolution, and in characterizing its sensitivity to x-rays with different photo-cathode materials.

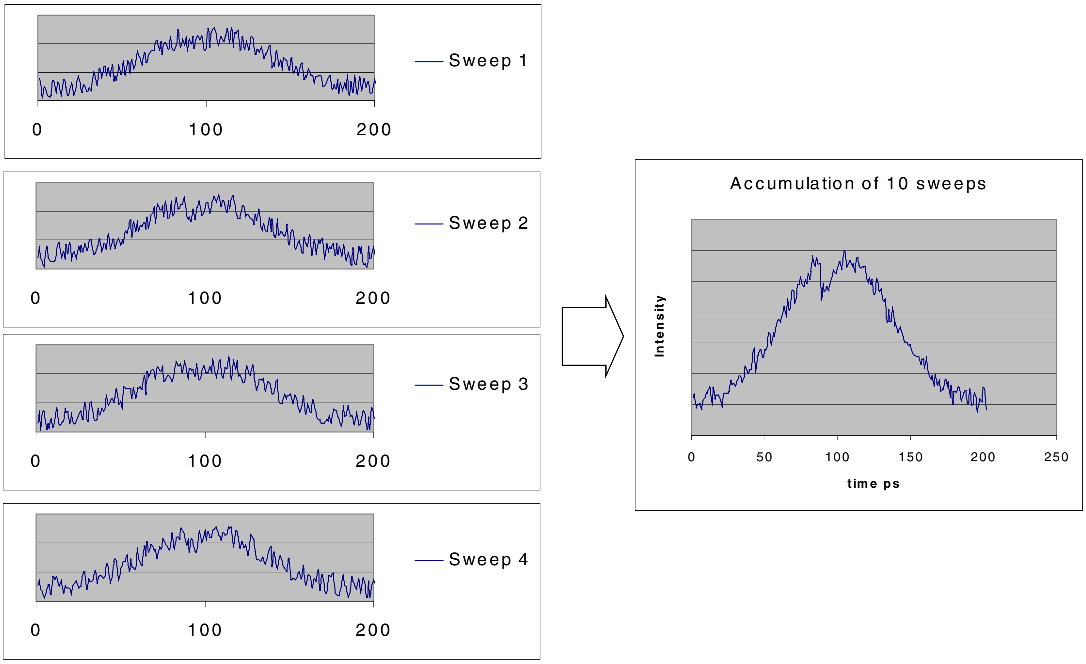

Figure 1. Reduction of noise by accumulating sweeps requires synchronization of the sweep to the event being recorded (simulation).

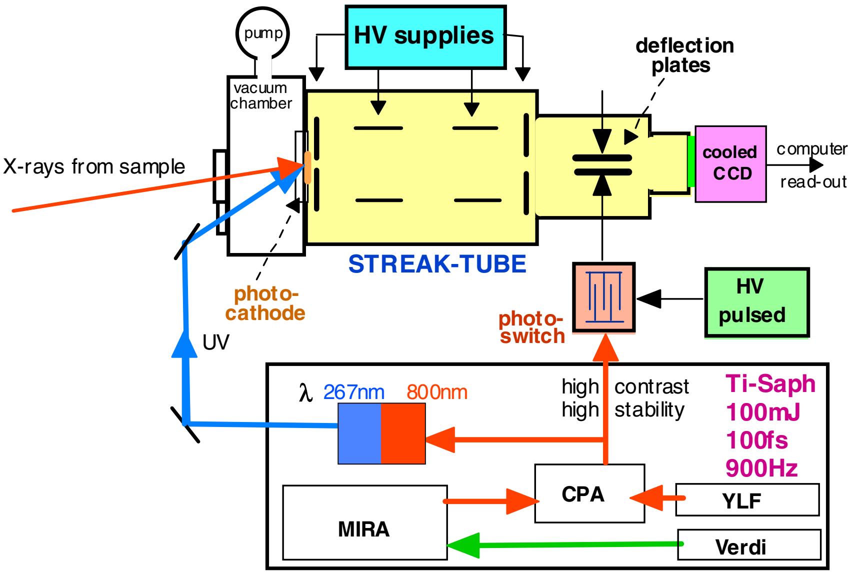

Figure 2. Layout of jitter free laser triggering of the photo-conductive switch.

2. Description

Ultra-short pulse laser light at 800 nm is used to illuminate a photoconductive switch. The photoconductive switch then changes to a low impedance state allowing the capacitance of the streak camera sweep plates to be rapidly charged. The resulting rapid rise time on the sweep plates gives the fast time resolution. The perfect registering of successive sweeps is determined ultimately by the width of the laser pulse and is important when accumulating multiple sweeps. The temporal performance of the streak tube is then monitored by shining ultra-short pulse light at the third harmonic of the laser (267 nm) onto the photocathode (figure 2).

2.1. *Streak tube*

The streak tube used is manufactured by Photonis (model no P860X/D2) [16]. The output screen of the streak tube is coupled via two fibre optic windows to a Peltier cooled CCD camera from Princeton Instruments (model no TE/CCD-1242-E/FGO with Micromax controller). The deflection sensitivity at the phosphor screen is 27 μm V^{-1}. The nominal value for acceleration field from the photocathode is 5 kV mm^{-1} (i.e. 15 kV/3 mm). The extraction field has been operated reliably at above 7.5 kV mm^{-1} (though without improvement on its time resolution).

The single shot time resolution for light at 267 nm was determined by exposing the camera to a small number of laser

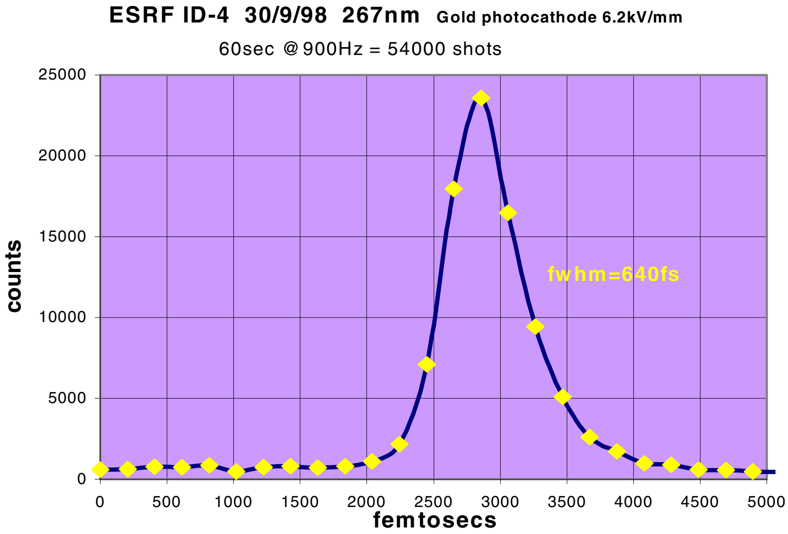

Figure 3. Pulse recorded by the streak camera of 54 000 successive laser pulses of 100 fs duration at 267 nm.

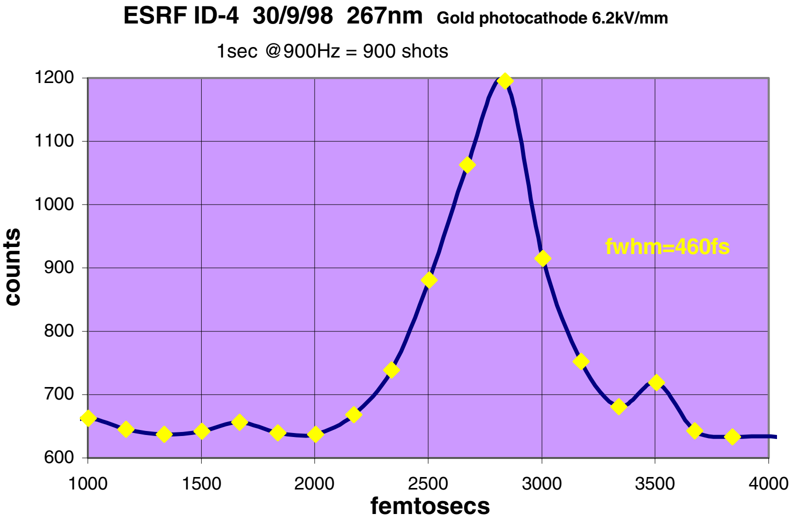

Figure 4. Pulse recorded by the streak camera of 900 successive laser pulses of 100 fs duration at 267 nm.

pulses at the third harmonic of the Ti:sapphire laser. The jitter of the sweep for a small number of pulses (900) over a short period of time (1 s) was assumed to be negligible. The trace observed on the CCD detector is shown in figure 4, indicating a time resolution FWHM of about 500 fs. A streak tube of such high temporal resolution is also reported in [17].

2.2. *Photoconductive switches*

The photoconductive switches are made from wafers of GaAs by Fast Light (Paris). The surface layer is passivated in order to increase the carrier lifetime and reduce the chance of breakdown in the post discharge period. An inter-digitated gold electrode structure is deposited onto the switch to increase the conductivity during the discharge period. The minimum spacing of the electrode structure is about 1.7 mm. Below this gap spontaneous surface discharging becomes a problem at the working voltages required to achieve the highest sweep speeds. The device is about 1 cm^2 in area and operates in air.

2.3. *Sweep circuit*

The sweep circuit is shown in figure 6, giving in these conditions a sweep speed of 125 fs/pixel (5.5 ps mm^{-1}). The circuit allows the single switch to initiate a rapid voltage ramp on the sweep plates in opposite directions so that the field applied due to the sweep plates is purely transverse. A pair of pulsed high-voltage power supplies applies the voltages to be discharged to the photoconductive switch about 500 ns prior to the rapid discharge. This dramatically reduces the chance of spontaneous discharge of the switch due to instability of the potential distribution within the bulk of the photoconductor. Figure 7 shows diagrammatically the voltage waveform on the sweep plates.

2.4. *Laser layout and synchronization*

The laser used to trigger the photoconductor and generate a pulse to excite the photo-cathode consists of a titanium sapphire ultra-short pulse oscillator amplified in a regenerative

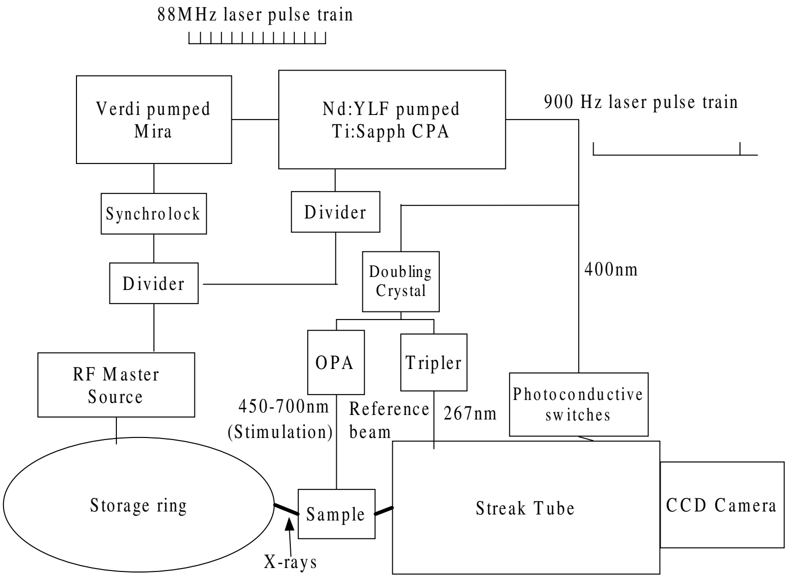

Figure 5. Synchronization of laser triggering to the x-ray pulses from the ESRF storage ring.

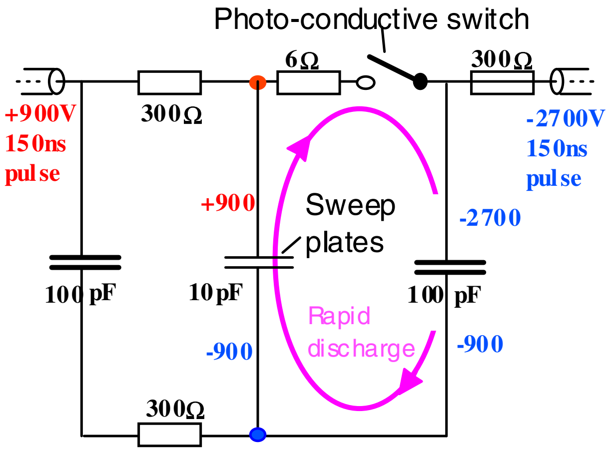

Figure 6. Electrical circuit producing the laser triggered voltage ramp on the streak tube sweep plates.

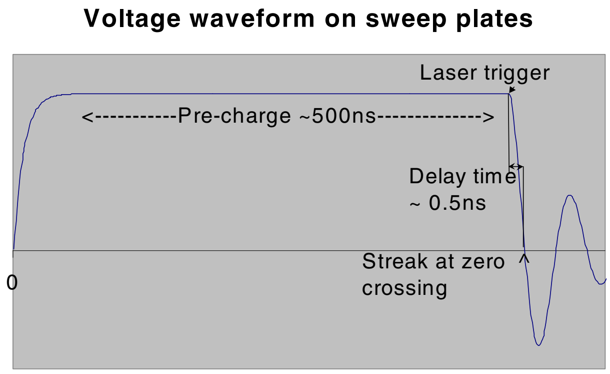

Figure 7. Voltage applied to the sweep plates by the pre-pulse supply and laser triggering.

amplifier synchronized to the ESRF electron storage ring that produces the x-rays (figure 5). The oscillator is a MIRA laser pumped by a 5 W Verdi laser, both supplied by Coherent Inc. Pulses from the MIRA are synchronized to the x-ray pulses of the synchrotron by phase locking the MIRA cavity to the fourth sub-harmonic of the RF clock, used to accelerate the electron bunches. The phase locking is achieved using a circuit called Synchro-lock also provided by Coherent. The regenerative amplifier (with associated stretcher and compressor in a chirped pulse amplification (CPA) arrangement [18] and its 12 W Nd:YLF pump laser were supplied by BM Industries (now THALES Laser). Ultra-short pulses at 800 nm are generated at a frequency of 900 Hz with a pulse length of about 100 fs and an energy of up to 800 μJ. This energy is used to pump an optical parametric oscillator and amplifier. The transmitted energy wasted by the parametric amplifier is used both to illuminate the photoconductive switch (about 100 μJ) and also to generate short pulses at 267 nm by frequency doubling and then frequency mixing the fundamental and second harmonic. The pulses at 800 nm and 267 nm pass through adjustable delay lines in order to achieve correct synchronization.

2.5. *Laser stability*

Fluctuations in the laser pulse energy or amount of pre-pulse/amplified spontaneous emission arriving at the photoconductive switch will lead to variations in the synchronization of the streak tube sweep. The most critical part of the laser beam alignment is in the regenerative amplifier, where three laser beam axes must be correctly superposed. These are the axes defined by

(i) the cavity itself,
(ii) the pump beam and
(iii) the injected beam.

Variations in the superposition of these axes may be caused by movements of mirror mounts or due to air motion in the beam paths. The use of stable mirror mounts limits movement of the mirrors to very slow drifts due to heating of the optical table. Short-term variations (0.1–10 Hz) are mainly due to

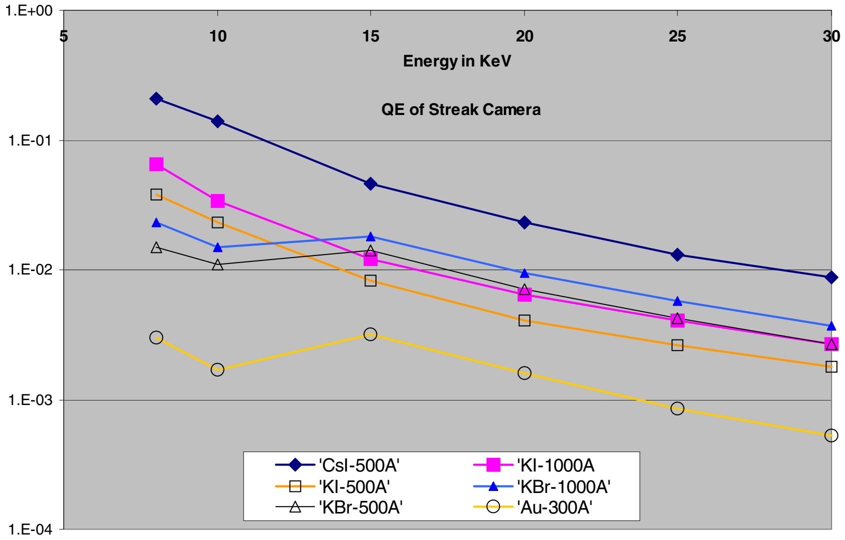

Figure 8. Relative sensitivity of different photo-cathode materials.

air turbulence/currents in the beam paths. The most critical parts are where the laser beam diameter is large or where a beam makes many passes. A great improvement in the laser stability (1.2% rms to <0.5% rms) was achieved by making sure any heat sources on the table were water cooled with water at a controlled temperature from a closed cycle cooler. The whole table is enclosed by Perspex sheets and the critical beam paths (YLF laser pump beam, and regenerative cavity) are enclosed in beam pipes. Care must be taken that power from the YLF pump beam transmitted by the Ti:sapphire crystal is absorbed away from the regenerative amplifier cavity so as not to cause air turbulence within the cavity. A saturable absorber is placed in the laser beam path to the photoconductive switches to reduce the amount of amplified spontaneous emission. The saturable absorber consists of a 1 mm thick sheet of RG850 Schott glass filter. The beam is focused through the filter as a line focus of about 10 mm × 0.1 mm and the filter is held in an aluminium mount so as to optimize cooling of the filter and avoid thermal degradation of the filter.

3. Causes of synchronization jitter

As can be seen from figure 7, the time at which the streak passes through the centre of the output screen is at some delayed time with respect to the photo-triggering of the photoconductive switch. This delay is due to the source impedance of the discharge circuit and the load capacitance of the sweep plates. If this delay time fluctuates it will lead to jitter in the output sweep. This jitter arises from fluctuations in the source impedance of the discharge circuit. While the source impedance is predominantly inductive it does have a component due to the small but finite ‘on’ impedance of the photoconductive switch. This impedance itself is determined by the resistance of the switch in the illuminated situation, which in turn depends on the carrier density and the number of illuminating photons incident on the photo-switch. There may also be variations in the inductive component of the photoconductive switch due to changes in the current path at different conductivities. We can therefore see that variations in laser pulse energy incident on the photoconductive switch will give rise to timing jitter. A further cause of jitter is the presence of laser light prior to the main laser pulse. This arises due to amplified spontaneous emission amplified in the regenerative amplifier and due to imperfect switching of the regenerative amplifier Pockels cell. The contribution to the jitter from this pre-pulse emission can be reduced to a negligible level by the use of the saturable absorber. A contrast ratio of the energy in the pre-pulse to the energy in the main pulse of better than 2×10^4 can routinely be achieved.

4. Results

The relative sensitivity of different photocathode materials was measured with the streak camera operated in static mode, that is to say without a sweep voltage applied to the sweep plates. The intensity measured by the CCD camera with a calibrated x-ray flux incident on the photo-cathode allowed the relative quantum efficiencies of the different materials to be determined. The x-ray flux incident on the photo-cathode from the ESRF synchrotron consisted of a train of pulses at about 100 MHz with a pulse length of about 100 ps. Though for this measurement the time structure was not important for the measurement of the streak camera, it is known that the streak tube phospor sensitivity is reduced when stimulated with short pulses. The results of these measurements are shown in figure 8 and are in agreement with previous characterizations of x-ray photocathodes [19, 20].

The tube operating in scanning mode as shown in figure 2 with short pulse laser excitation of the photocathode allowed a measure of the temporal resolution achievable in multi-shot mode. Exposure times of the photocathode of up to 1 minute at a laser pulse repetition rate of 900 Hz led to the accumulation of up to about 50 000 pulses (figure 3). The Peltier cooled CCD detector allowed the image from the photo-cathode to be integrated and read out at the end of the exposure period. The camera is typically operated at −10 degrees centigrade (a limit to the lowest temperature achievable is imposed by the thermal load provided by the coupling to the streak tube

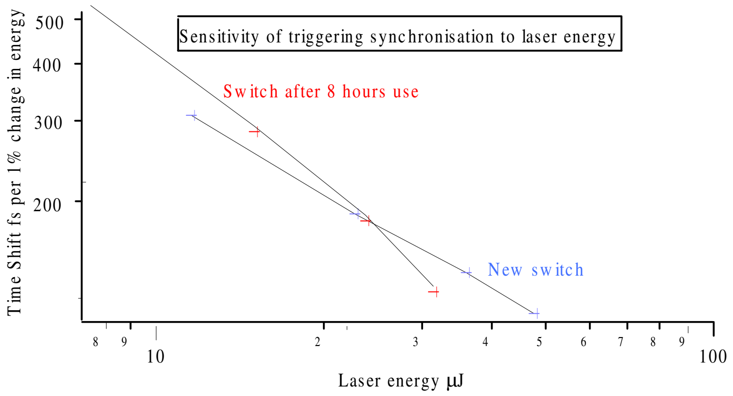

Figure 9. Change in delay time from arrival time of the laser pulse to zero crossing of the sweep voltage as a function of laser energy.

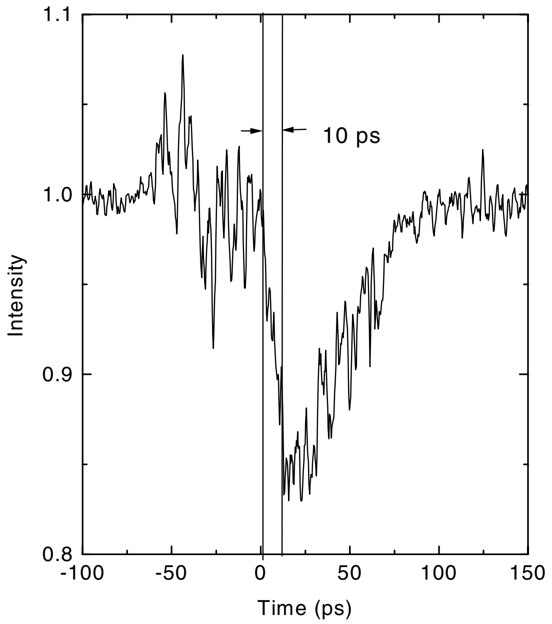

Figure 10. Ultra-fast modulation of the x-ray diffraction from a GaAs crystal after disordering induced by a 100 fs laser pulse at 800 nm.

itself via the fibre optic coupling windows. Without using index matching grease a lowest temperature of −29 °C can be achieved. Thermal noise at −10 °C prevents integration periods much longer than 1 minute. The overall time resolution is the convolution of the single shot resolution of the streak tube, the jitter in the sweeping of the streak plates and the spatial resolution of the fibre-optic relay and CCD detector assembly. The jitter originates mainly from fluctuations in the laser energy. The sensitivity of the sweep synchronization to a 1% change in laser energy is shown in figure 9 as a function of laser energy. Note as the laser energy is increased the sensitivity to energy fluctuations decreases due to the reduction of the contribution of the switch impedance to the total discharge impedance. By reducing the fluctuations of the laser energy, the contribution of the jitter to the overall time resolution seen in figures 3 and 4 becomes small. We believe the 500 fs time resolution observed with a 1s exposure represents the ultimate time resolution of the camera [10].

5. Experimental use

The above measurements of the temporal resolution were achieved with ultraviolet illumination of the photocathode. The effective resolution for x-rays should be determined in the observation of a rapid x-ray event. The rapid surface disordering of Ga As was used as a test. This experiment had been performed using a laser produced x-ray plasma [21]. A rapid decrease in the diffracted signal on the positive side of the rocking curve was observed (figure 10). An x-ray energy of 11 keV was used. The time scale of the event observed was around 10 ps, though we believe this to be limited by the configuration of the sample itself rather than the ultimate time resolution of the streak camera. The high noise level on the trace is due to the high level of thermal readout noise during the experiment. The CCD camera was operated just above 0 °C for this experiment. By cooling the camera to much lower temperatures and optimizing the sample geometry we hope to see a much faster event demonstrating the ultimate time resolution of the device for x-rays. The ultimate time resolution possible in x-ray diffraction experiments is limited by transit time dispersion from the different lattice planes [22].

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