Final Progress Report for
DE-FG03-02ER15285

CONTINUING THE DEVELOPMENT OF A 100 FEMTOSECOND X-RAY DETECTOR

The grant is a one-year renewal for a two-year grant titled "100 femtosecond X-ray Detector" that was awarded to the PI (Zenghu Chang) in 2000 when he was at the University of Michigan. In 2001, the original grant was transferred to Kansas State University with the PI. The detector is an x-ray streak camera running in accumulation mode for time resolved x-ray studies at the existing third generation synchrotron facilities and will also be used for the development and applications of the fourth generation x-ray sources. We have made significant progress on both the detector development and its applications at Synchrotron facilities.

1. PATENTS, PUBLICATIONS AND AWARD

1.1 Patents

(1). Bing Shan, Chun Wang, Zenghu Chang, "*Producing 4mJ, 25 fs Pulses from a kHz Laser Using A Single Stage Multipass Amplifier*", Submitted to US Patent Office, 2003.

(2) Zenghu Chang, Bing Shan, "*Producing Energetic, Tunable, Coherent X-rays with Long Wavelength Light*", Submitted to US Patent Office, April, 2001.

1.2 Publications

(1). S. L. Johnson, P. A. Heimann, A. G. MacPhee, A. M. Lindenberg, O. R. Monteiro, Z. Chang, R. W. Lee, and R. W. Falcone, "*Bonding in liquid carbon studied by time-resolved x-ray absorption spectroscopy*", Phys. Rev. Lett., **94**, 057407 (2005).

(2). M. F. DeCamp, D. A. Reis, A. Cavalieri, P. H. Bucksbaum, R. Clarke, R. Merlin, E.M. Dufresne, and D. A. Arms, A. Lindenberg and A. Macphee, Z. Chang, J. S. Wark and B. Lings**,** *"Transient Strain Driven by a Dense Electron-Hole Plasma,"* Phys. Rev. Lett. **91**, 165502 (2003).

(3). S. L. Johnson, P. A. Heimann, A. M. Lindenberg, H. O. Jeschke, M. E. Garcia, Z. Chang, R.W. Lee, J. J. Rehr, and R. W. Falcone, "*Properties of liquid silicon observed by time-resolved x-ray absorption spectroscopy*", Phys. Rev. Lett. **91**, 157403 (2003).

(4). Jinyuan Liu, Jin Wang, Bing Shan, Chun Wang, Zenghu Chang, "*An accumulative x-ray streak camera with sub-600 fs temporal resolution and 50 fs timing jitter*", Applied Physics Letters **82**, 3553 (2003).

(5). J. Liu, J. Wang, B. Shan, C. Wang, and Z. Chang, *"X-ray streak camera with 30-fs timing jitter*," Proceedings of SPIE **5194**, 123 (2003).

(6). J. Liu, A. G. MacPhee, C. Liu, B. Shan, Z. Chang and J. Wang, *"New approach to jitter reduction of an x-ray streak camera in accumulation mode"*, Proceedings of SPIE, **4796** 184 (2002).

(7). A. M. Lindenberg, I. Kang, S. L. Johnson, R. W. Falcone, P. A. Heimann, Z. Chang, R. W. Lee, J. S. Wark, *"Coherent control of phonons probed by time-resolved x-ray diffraction"*, OPTICS LETTERS **27**, 869 (2002).

(8). B. Shan, Z. Chang, *"Dramatic extension of the high-order harmonic cutoff by using a long-wavelength pump"*, PHYS. REV. A **65**, 011804(R) (2002).

(9). B. Shan, Xiao-Min Tong , Zengxiu Zhao, Zenghu Chang and C. D. Lin, *"High harmonic cutoff extension of O_2 molecule due to ionization suppression"*, PHYS. REV. A, **66** 061401(R) (2002).

(10). B. Shan, A. Cavalieri, Z. Chang, "*Tunable high harmonic generation with an optical parametric amplifier"*, Appl. Phys. B **74**, s23-s26 (2002).

(11). P. A. Heimann, A. M. Lindenberg, I. Kang, S. Johnson, T. Missalla, Z. Chang, R.W. Falcone, R.W. Schoenlein, T.E. Glover, H.A. Padmore, *"Ultrafast X-ray diffraction of laser-irradiated crystals"*, Nuclear Instruments & Methods in Physics Research Section Accelerators Spectrometers Detectors and Associated Equipment **467**, Part 2, 986 (2001).

(12). J. S. Wark, A. M. Allen, P. C. Ansbro, P. H. Bucksbaum, Z. Chang, M. DeCamp, R. W. Falcone, P. A. Heimann, S. L. Johnson, I. Kang, H. C. Kapteyn, J. Larsson, R. W. Lee, A. M. Lindenberg, R. Merlin, T. Missalla, G. Naylor, H. A. Padmore, D. A. Reis, K. Scheidt, A. Sjoegren, P. C. Sondhauss, M. Wulff, *"Femtosecond X-ray diffraction: experiments and limits"*, Proceedings-of-the-SPIE--The-International-Society-for-Optical-Engineering **4143**, 26 (2001).

1.3 Conference presentations

(1). Bing Shan, Zenghu Chang, Jinyuan Liu, Chun Wang, Jin Wang, A multishot accumulation x-ray streak camera with subpicosecond temporal resolution", *CLEO/QELS 2003***,** CThM20, Baltimore, MD (2003).

(2). J. Liu, A.G.MacPhee, C.Liu, B.Shan, Z.Chang and J .Wang, "New approach to jitter reduction of an x-ray streak camera in accumulation mode", SPIE' 47th annual meeting. Paper number: 4796-45, Seattle, WA (2002).

(3). A.M. Lindenberg, I. Kang, S.L. Johnson, R.W. Falcone, P.A. Heimann, T. Massala, Z. Chang, R.W. Lee, J.S. Wark, “Coherent phonon spectroscopy using time-resolved x-ray diffraction”, *CLEO/QELS 2001*, QTuH4, Baltimore, MD, May 6-11 (2001).

(4). Z. Chang, W. Peng, B. Shan, J. Liu, A.M. Lindenberg, S.L. Johnson, R.W. Falcone, P.A.Heimann, H. Padmore, R.W. Lee, “Ultrafast X-ray Streak Camera”, Workshop on femtosecond x-ray Science, Berkeley, CA, October 17-20 (2000).

1.4 Award

Halbach Award for Outstanding Instrumentation at the Advanced Light Source, Team award, Lawrence Berkeley National Laboratory, 2000.

2. STUDENT, POSTDOCTORAL FELLOW AND VISITING SCHOLAR SUPPORTED

2.1 Student

Mahendra Shakya, who has worked on the x-ray streak camera since May 2002. He received a Masters degree in December 2003 at Kansas State University. His Masters degree thesis is entitled “*Development of an ultrafast accumulative x-ray streak camera.”* Mr. Shakya is now a PhD candidate at Kansas State University.

2.2 Postdoctoral fellow

Dr. Bing Shan at Kansas State University, who has worked on the streak camera project since 2001. Dr Shan is now an assistant research professor at Kansas State University.

2.3. Visiting scholar

Jinyuan Liu while he was at the University of Michigan. At the present, Mr. Liu is with Argonne National Laboratory.

3. DESCRIPTION OF ACCOMPLISHMENTS

3.1 Streak camera development

(1). A streak camera operating under ultrahigh vacuum was developed. To reach our 100 fs resolution goal, we proposed operating the streak tube in a UHV housing to increase the electric field in the cathode to the anode region. To test our idea, a streak camera housing with $2x10^{-9}$ torr vacuum was built with which we can run the streak tube at 30 kV/mm. Under such a high field, the temporal resolution of the streak tube using a CsI photocathode should be 100 fs. We are working on improving the vacuum and the cathode/anode assembly designed to further increase the field.

(2). We revealed a mechanism that causes deflection aberration. We demonstrated that the effects of the aberration could be significantly reduced by eliminating electrons with large divergence angles.

(3). We demonstrated that by using a fast response photoconductive switch and deflection plates, the jitter and the temporal resolution were reduced for a typical kilohertz laser.

The most recent configuration of the streak camera is shown in fig. 1.

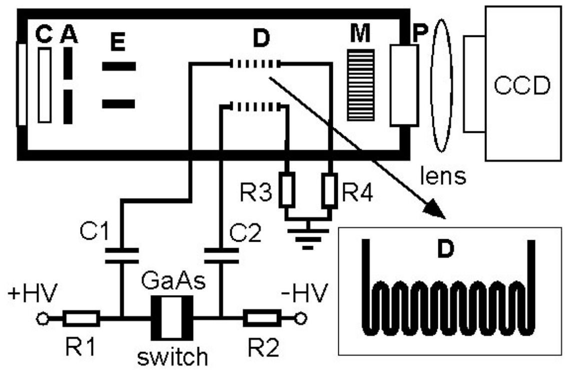

Fig. 1. Schematic of the x-ray streak camera. C: photocathode; A: anode, E: electrostatic lens; D: meander-type deflection plate; M: microchannel plate; P: phosphor screen; C_1, C_2: DC blocks; R_1, R_2: 1 MΩ resistors; R1, R2: 50 Ω matching resistors; ±HV: high voltage bias.

The achieved temporal resolution in accumulation mode is 590 fs, which is much better than the 2 picosecond resolution achieved when the project started. The result is shown in figure 2.

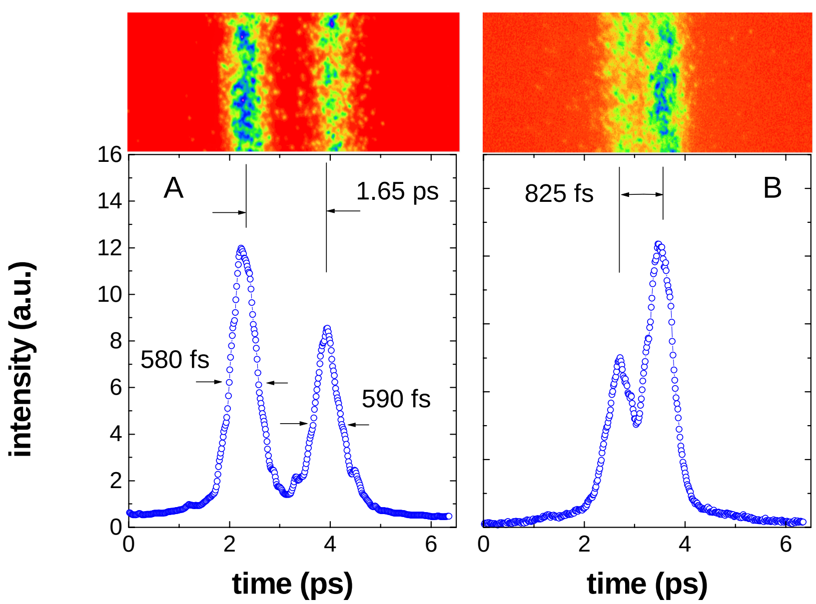

Fig. 2. Averaged lineout of the streak images with corresponding actual images (top) of two 30 fs UV pulses separated by 1650 fs (A) and 825 fs (B).

(4). We demonstrated that the cutoff photon energy of high order harmonic generation could be extended by using a long wavelength field from an optical parametric amplifier. This paved the way for producing femtosecond keV x-rays for streak camera calibration and for other applications.

3.2 Streak camera applications

So far, we have used the streak camera at the ALS, Lawrence Berkeley National Laboratory and at the APS, Argonne National Laboratory. A new camera based on our design is under construction for the Stanford SPPS generation source.

(1) Application of the streak camera at the Advanced Light Source, Lawrence Berkeley National Laboratory

We have continued the collaboration with the team led by Prof. Roger Falcone at the University of California, Berkeley. A streak camera was set up on a dedicated femtosecond x-ray beam line. Our streak camera has been used to study coherent phonon dynamics of semiconductors.

In one experiment, time-resolved x-ray diffraction with picosecond temporal resolution is used to probe the product state of a coherent control experiment in which a single acoustic mode in a bulk semiconductor is driven to a large amplitude or canceled out. It is demonstrated that by shaping ultrafast acoustic pulses one can coherently control the x-ray diffraction efficiency of a crystal on the time scale of a vibrational period, with application to coherent switching of x-ray beams. The results are shown in figure 3.

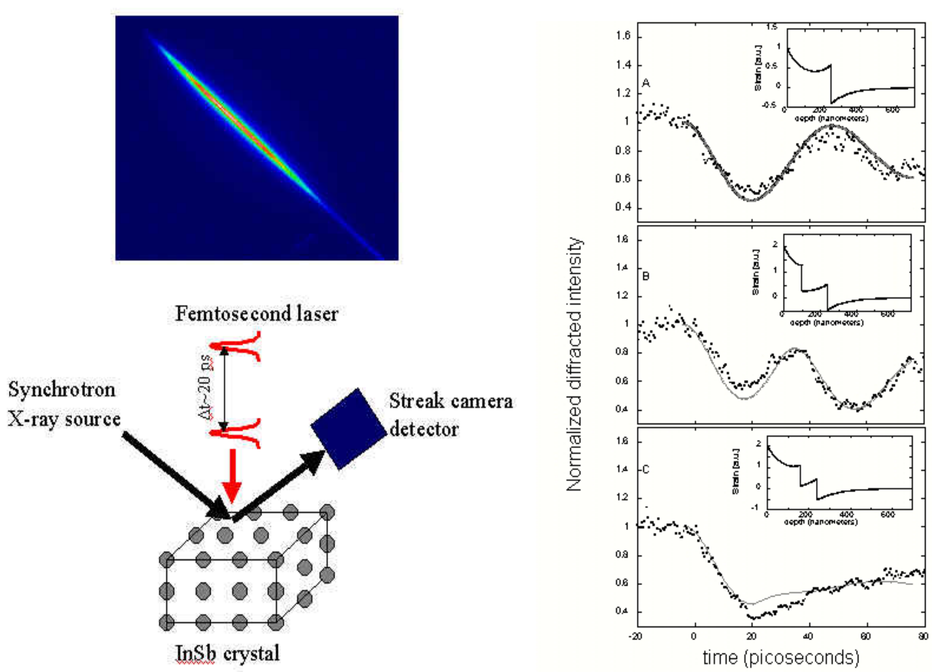

Fig. 3. (**A**) Single pulse excitation, probing the $q=4\times10^{5}cm^{-1}$ acoustic phonon mode. (**B**) Enhancement of the $q=4\times10^{5}cm^{-1}$ mode using 2-pulse excitation with a relative delay of 35 ps, equal to one vibrational period. (**C**) Cancellation of $q=4\times10^{5}cm^{-1}$ mode using 2-pulse excitation with a relative delay of 18 ps, or 1/2 a vibrational period. Time-resolved diffracted intensity is normalized to one for t<0. Solid line corresponds to simulations. Insets: Generated acoustic pulse profile for each case, respectively, at time t=60 ps.

(2) Application of the streak camera at the Advanced Photon Source, Argonne National Laboratory

Our streak camera has been applied to the MHATT-CAT beam line in collaboration with Prof. P. Bucksbaum's group from the University of Michigan. In one of the experiments, picosecond switching of x-rays using the Borrmann Effect was studied. The Ge crystal is oriented in the Laue geometry to diffract from the asymmetric (202) diffraction planes. At the crystal output there exists two diffracted beams; a forward diffracted and a deflected diffracted beam. Coherent acoustic phonons are impulsively generated in a 280 μm thick sample of (001) Ge using a 50fs, 0.75mJ, 800 nm laser operating at 1kHz.Figure 4 shows time-resolved diffraction data from the x-ray streak camera. The top figure is the streak image of an x-ray pulse after traversing the unperturbed crystal. The effective x-ray pulse width emitted from the APS is ~100ps FWHM. Upon laser excitation, the disturbed crystal switches the x-ray intensity of the forward-diffracted beam. Up to 75% of the incident x-ray intensity is switched off in <40 ps, effectively reducing the x-ray pulse width to ~60ps. This energy loss is recovered by the deflected diffracted beam, which increases at the same rate. Rotating the crystal to diffract from the opposite asymmetry produces the opposite effect; the increase of x-ray intensity of the forward diffracted beam is on a 40 ps timescale.

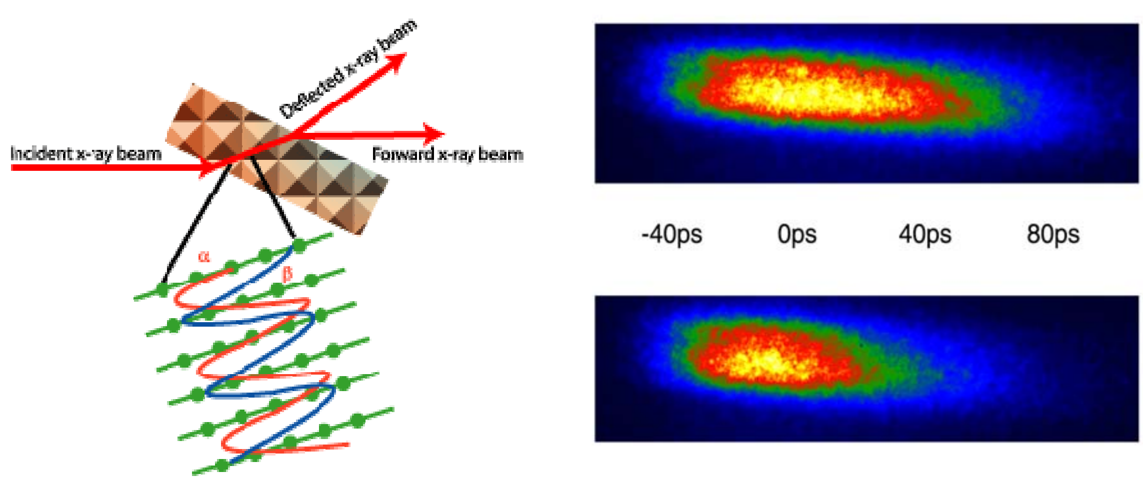

Fig. 4. Streak images of the transmitted x-ray pulse. Undisturbed crystal (top), Laser heated crystal (bottom). 0ps corresponds to the laser arrival time.

We started a collaboration with Dr. Jin Wang's group at the Advanced Photon Source, Argonne National Laboratory. The idea is to use the streak camera for the 4th generation source development.