

Femtosecond physics

A team at Berkeley's Advanced Light Source has shown how a laser time-slicing technique provides a path to experiments with ultrafast time resolution.

Femtosecond synchrotron radiation at Berkeley's Advanced Light Source

A Lawrence Berkeley National Laboratory (Berkeley Lab) team drawing its members from the Materials Sciences Division (MSD), the Center for Beam Physics in the Accelerator and Fusion Research Division, and the Advanced Light Source (ALS) has succeeded in generating 300-femtosecond pulses of synchrotron radiation at the ALS synchrotron radiation machine.

Though this "proof-of-principle" experiment made use of visible light on a borrowed beamline, the laser "time-slicing" technique at the heart of the demonstration will soon be applied in a new bend-magnet beamline designed explicitly for the production of femtosecond pulses of X-rays to study long-range and local order in condensed matter with ultrafast time resolution. *An* undulator beamline based on the same technique has been proposed that will dramatically increase the flux and brightness.

The use of X-rays to study the course of solid-state phase transitions, the kinetic pathways of chemical reactions, and the efficiency and function of biological processes on the fundamental time scale of a molecular vibration (about 100 fs) is an emerging field of research.

Ahmed H. Zewail of Caltech was awarded the 1999 Nobel Chemistry Prize for showing how rapid laser techniques can reveal how atoms move during chemical reactions.

Pump-probe techniques in which a pump pulse stimulates the process followed by a probe pulse to examine it at intervals thereafter constitute a common way to follow the dynamics of ultrafast processes with infrared and visible lasers. However, there is a dearth of ultrafast X-ray sources to provide structural information on this time scale. The pulse length of synchrotron radiation, for example, is limited by the bunch length of the electron beam, about 30 ps at the ALS.

Ultra-short pulses

A solution to the bunch-length problem was described four years ago by Alexander Zholents and Max Zolotarev of the Center for Beam Physics. In short, a high-power, femtosecond laser synchronized with the electron bunches passes collinearly with an electron bunch through an insertion device (undulator or wiggler) as in a free-electron laser. The high electric field of the shorter laser pulse modulates a portion of the longer electron bunch, with some electrons gaining energy and some losing energy.

The condition for optimum energy modulation occurs when the laser wavelength matches the wavelength of the fundamental emission from the insertion device. Subsequently, when the energy-modulated electron bunch reaches a section of the storage ring with a non-zero dispersion, a transverse separation occurs, resulting in slices of the bunch roughly as long as the laser pulse. A collimator or aperture selects the synchrotron radiation from the displaced bunch slices.

The team led by MSD's Robert Schoenlein implemented the time-slicing scheme by using a high-power titanium-sapphire laser to modulate the electron beam in a 16-cm-period wiggler already in straight section 5 of the 12-fold symmetric storage ring. Bend

magnets between the wiggler and the beamline provide horizontal dispersion and the synchrotron radiation, and a test chamber on an existing bend-magnet beamline in the curved sector after straight section 6 records the femtosecond pulses (see Figure 1).

Femtosecond time structure

They verified the femtosecond time structure by imaging visible light from the beamline onto a nonlinear optical crystal along with a delayed 50-femtosecond cross-correlation pulse from the laser system and then counting photons at the sum frequency as a function of delay between the modulating and the cross-correlation laser pulses. An adjustable knife edge located in the beamline at an intermediate image plane provided a means to select radiation from different transverse regions of the electron beam. In this way, they measured a dark 300-femtosecond hole in the central cone of the synchrotron radiation and a bright 300-femtosecond peak in the wing of the synchrotron radiation (Figure 2). This success was the result of a synergistic collaboration between two complementary groups at Berkeley lab working at the ultrafast science frontier—the Center for Beam Physics headed by Swapn Chattopadhyay and the Femtosecond Spectroscopy Group led by Berkeley Lab Director Charles Shank. As part of a growing femtosecond x-ray science program at the ALS, new beamlines are under construction and proposed under the leadership of Schoenlein and Roger Falcone of the University of California, Berkeley. A bend-magnet beamline with an anticipated completion date of June 2000 has a performance goal of 100-fs pulses at a repetition rate of 5 kHz with a flux of about 10^5 photons/second/0.1% bandwidth and a brightness of about 10^8 photons/second/mm²/mrad²/0.1% bandwidth for photon energies up to 10 keV. A proposed undulator beamline would increase the flux and brightness by a factors of about 100 and 10,000, respectively. An in-vacuum device, the planned undulator has a 5-mm gap, almost a factor of three smaller than the current smallest magnetic gap (14 mm) and nearly a factor of two smaller than the narrowest vacuum chamber (9 mm) in the ring. A vertical rather than horizontal dispersion would also be used. A complete mini-beta lattice with large vertical dispersion bumps is being designed to accommodate these features.

References

R. W. Schoenlein, S. Chattopadhyay, H. H. W. Chong, T. E. Glover, P. A. Heimann, C. V. Shank, A. A. Zholents, and M. S. Zolotarev,” *Science* **287**, 2237 (2000).

Captions

Schematic showing how the laser bunch-slicing technique was used to produce femtosecond pulses of synchrotron radiation at Berkeley's Advanced Light Source (ALS): (left) laser/electron beam interaction in resonantly-tuned wiggler; (centre) separation of accelerated femtosecond electron slice in a dispersive bend magnet; (right) generation of femtosecond x-rays in a bend-magnet beamline.

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Cross-correlation between a delayed laser pulse and the synchrotron radiation shows that (left) light from the central core of the electron bunch with a dark femtosecond hole and (right) light from a horizontal wing of the electron bunch with a bright femtosecond peak.

Solid lines are from a model calculation of the spatial and temporal distribution of the energy-modulated electron bunch following propagation through 1.5 arc-sectors at the ALS

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