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Ultrafast X-rays from 3rd Generation Synchrotrons

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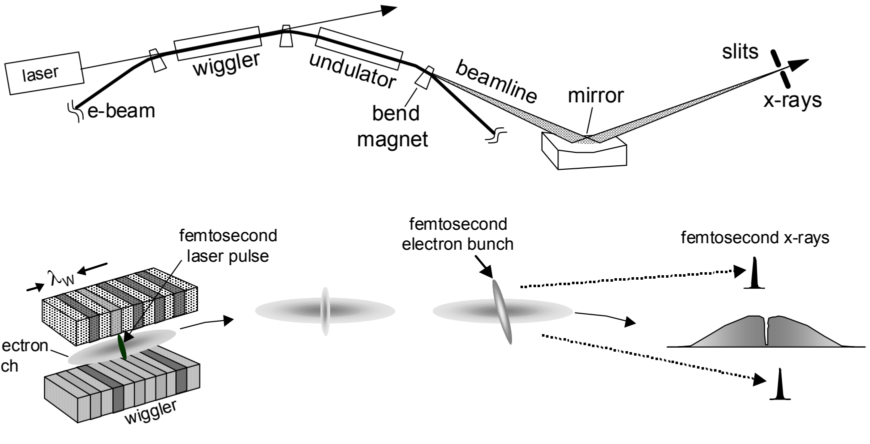
An important new area of scientific research in chemistry, physics, and biology is the investigation of ultrafast structural dynamics in condensed matter using femtosecond x-ray pulses. X-rays are powerful probes of atomic and electronic structure since they interact with core electronic levels, and can therefore provide direct information about relative atomic positions, coordination, and bonding geometry. Modern synchrotrons are the brightest sources of x-rays available, and have proven to be very powerful tools for probing the "static" or time-averaged structure of matter. Techniques such as x-ray diffraction, extended x-ray absorption fine structure (EXAFS) and many others are widely used at such facilities to obtain structural information with atomic spatial resolution and meV energy resolution. However, the time resolution provided by synchrotrons is typically limited to several tens of picoseconds due to the length of the stored electron bunches. This is orders of magnitude longer than the fundamental time scale for atomic motion, dictated by an atomic vibrational period, ~100 fs. This talk will focus on present capabilities and future prospects for generating ultrafast x-rays from 3rd generation synchrotrons, and the applicability of such radiation for ultrafast x-ray science.

One promising scheme for generating femtosecond duration pulses of synchrotron radiation is based on manipulation of a stored (~30 ps) electron bunch with a femtosecond optical pulse[1]. The femtosecond laser pulse creates femtosecond time-structure on a long electron bunch by modulating the energy of an ultrashort slice of the bunch. Femtosecond synchrotron pulses are then generated from a bend-magnet or from a second insertion device (undulator or wiggler).



electron-photon interaction in wiggler
(A)

spatial separation dispersive bend
(B)

bend magnet (or undulator) beamline
(C)

Fig. 1. Schematic of method for generating femtosecond synchrotron pulses. (A) Femtosecond laser pulse interaction with the electron bunch in a permanent-magnet wiggler. (B) Transverse separation of modulated electrons in a dispersive bend of the storage ring. (C) Generation of synchrotron radiation from a bend-magnet (or undulator) and separation of the femtosecond synchrotron radiation at the beamline image plane.

Figure 1 illustrates the modulation and generation scheme. A femtosecond laser pulse co-propagates with the stored electron bunch through a wiggler (Fig. 1A). The high electric field of the laser pulse modulates the energy of the underlying electrons as they traverse the wiggler. The optimal interaction occurs when the central wavelength of the spontaneous emission from an electron passing through the wiggler matches the laser wavelength (FEL resonance condition). In addition, the transverse mode of the laser beam must match the transverse mode of the spontaneous radiation from the electron passing through the wiggler, and the laser spectral bandwidth must match the spectrum of the fundamental wiggler radiation averaged over the transverse mode.

By creating an energy modulation that is significantly larger than the beam energy spread, the transverse dispersion of the storage ring will cause a spatial displacement of the modulated electrons from the rest of the electron bunch (Fig. 1B). Finally, by imaging the synchrotron radiation from the displaced electrons to the experimental area, femtosecond x-rays can be separated from the long-pulse using an aperture (Fig. 1C). The time structure of the temporally incoherent synchrotron radiation is directly determined by the time structure of the electron bunch and is invariant over the entire spectrum of the synchrotron emission, from infrared to x-ray wavelengths. This technique has been developed at the Advanced Light Source (ALS), and the time structure of the visible synchrotron pulses has been directly measured via cross-correlation with a delayed pulse from the laser system[2,3]. An adjustable knife-edge located in the beamline at an intermediate image plane provides a means to select synchrotron radiation originating from different transverse regions of the electron beam.

Based on this approach, femtosecond x-ray beamlines are presently under construction at the ALS, the Swiss Light Source (SLS) and the BESSY ring in Berlin. This talk will provide an overview of the projected capabilities of these beamlines, and will discuss some of the practical limitations and issues associated with applying this radiation to ultrafast experiments.

One clear limitation of the approach described above is that it makes use of only a small fraction ($\sim 10^{-3}$) of the charge in a single electron bunch. Recently a number of 3rd generation synchrotron facilities have begun to explore the possibility of storing shorter electron bunches in a ring[4,5], or alternatively compressing the electron bunch duration in particular regions of the storage ring, combined with x-ray pulse compression[6]. This talk will provide a brief overview of this work and discuss some of the practical limitations, future prospects, and scientific applicability of these schemes.

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