Physics: Atomic and molecular physics
Physics: Lasers

Laser-driven x-ray sources

Ever since the invention of the microscope, one of the great trends of modern science has been toward resolving ever-finer detail in the study of matter. Since small objects generally move quickly (which simply follows from the dependence of inertia on mass), high spatial resolution alone is not sufficient to image such objects (for example, to take a magnified photograph of them with a camera). A short-duration flash of light (or fast shutter) is also necessary to prevent blurring of the image. While the millisecond duration of an ordinary camera is sufficient to freeze the action of a person running (meter-scale length), a strobe light with ultrashort pulse duration (1 femtosecond or 10^{-15} s) is required in order to resolve a moving atom (10^{-10}-m-scale length).

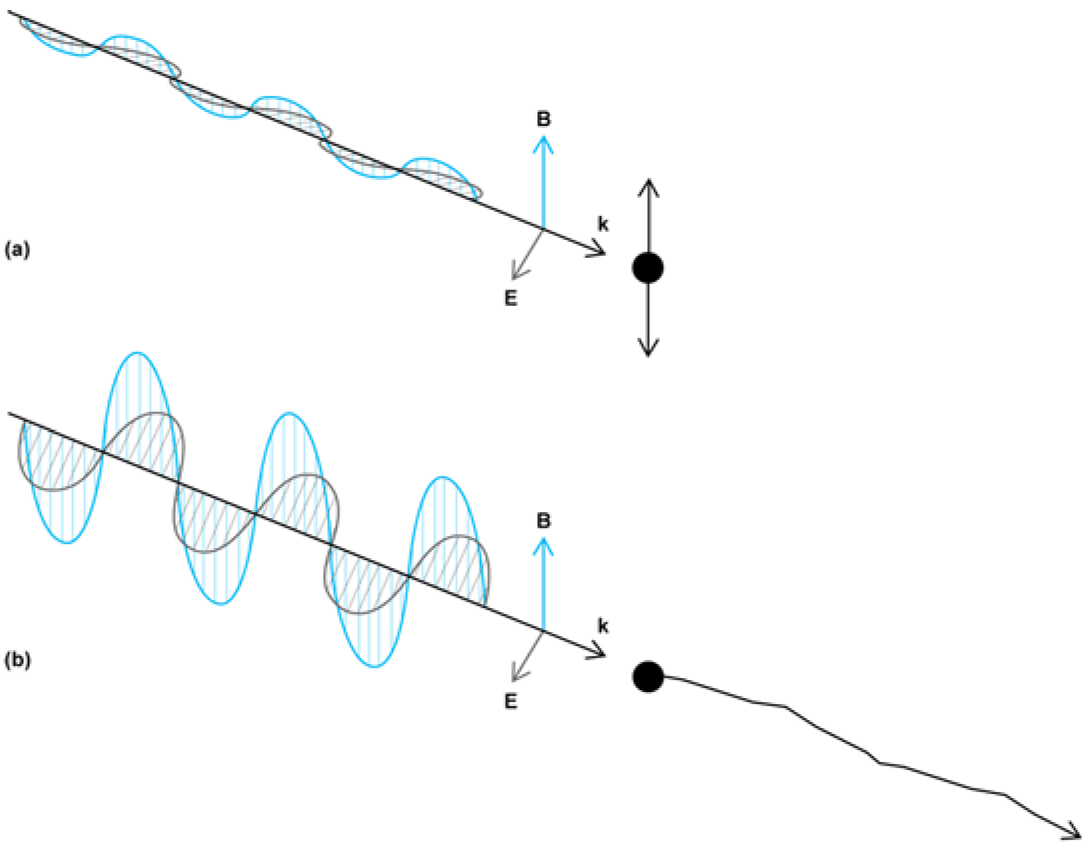
For this reason, the study of ultrafast molecular dynamics did not begin until the development of femtosecond-duration optical lasers in the late 1970s. However, direct time-domain measurements with femtosecond temporal resolution could be made with only micrometer-scale spatial resolution because of the relatively long wavelength (~1 micrometer) of optical light. Alternatively, direct measurements with atomic-scale spatial resolution could be made with x-rays from synchrotrons, but with only nanosecond temporal resolution, because of the relatively long duration of these sources. Now, with the development of a new generation of tabletop-size laser systems, it is feasible to generate femtosecond-duration x-ray pulses, which will allow high resolution to be achieved simultaneously in both space and time.

What makes these lasers so promising is that they can deliver both short pulses and high peak power. Because power is energy divided by time, when only a joule of energy is released over femtoseconds, it can produce a terawatt of power. This power can produce the highest light intensities on Earth, 10^{21} W/cm^2, by focusing the light to a spot size of the laser wavelength. Associated with these extreme power densities are the largest electric and magnetic fields ever produced, of the order of 10^{12} V/cm and 10^5 tesla (10^9 gauss), respectively. What permits solid-state lasers to generate such high fields is the chirped-pulse-amplification technique, invented in 1987. In order to prevent damage to the amplifiers, the laser light is first stretched in time, then amplified as a pulse with long duration, and thus with lower power, and lastly compressed to a short duration after the energy has been increased. Fields of this high strength can accelerate electrons to relativistic energies, which can then be used to convert light to short pulses of x-rays.

Electron motion in laser fields

Light is a wave with transverse electric and magnetic fields oscillating at the same frequency. At low laser power, electrons oscillate along the light's electric field (E) with a velocity (v) which is always very small compared to the speed of light (Fig. 1*a*). This motion is described by the equation $m(d\mathbf{v}/dt) = -e\mathbf{E}$, where m is the electron mass and e is the magnitude of its charge. At higher laser intensities, the electron velocity in a laser focus can reach close to the speed of light (c) and its mass (m) will increase due to relativistic effects. In this relativistic regime, one must also include an additional term in the equation of motion, which then becomes $m(d\mathbf{v}/dt) = -e[\mathbf{E} + (\mathbf{v}/c) \times \mathbf{B}]$. Thus, the light's magnetic field (*B*) will act to bend the electrons in the direction of light propagation, perpendicular to both *E* and *B* (Fig. 1*b*). With this additional force, the electron traces a figure-8, oscillating twice in the direction of the light wave for every single oscillation along the polarization direction (along *E*). This oscillating motion is then superimposed upon a steady drift in the direction of the light wave. Thus the motion is increasingly longitudinal as the light intensity is increased.

Fig. 1 Motion of an electron in a light wave. (*a*) In classical optics, the amplitude of the light wave is small, electrons oscillate in the direction of the electric field, *E*, at the light's frequency, and there is no displacement along the light's propagation direction, *k*. Only the electric field acts on the electron, and the electron-oscillation velocity is very small compared with the speed of light. (*b*) In relativistic optics, the amplitude of the light wave is very large, the light's magnetic field becomes important, and the combined action of the electric and magnetic fields pushes the electron forward. In this case, the electron velocity becomes close to the speed of light.



Laser focusing on solid targets

One way to make x-rays is by focusing an intense laser onto a solid target. When the relativistic electrons collide with the ions of the solid, they rapidly accelerate, causing the emission of bremsstrahlung radiation in the x-ray spectral region. This is just like a conventional x-ray tube, such as found in a dentist's office, except it is the laser's short-duration electromagnetic field that accelerates the electrons instead of the continuous electrostatic field between the anode and cathode of the x-ray tube. One of the problems with these x-rays is that they are produced in all directions simultaneously (4π steradians), and so their intensity decreases with the square of the distance from the source. They are also incoherent and deliver relatively long pulses, picosecond in duration. However, because of the simplicity of the method used to produce them, these x-rays have been used to study picosecond processes such as shock formation or melting by means of either x-ray absorption or diffraction.

Laser focusing on gaseous targets

Another way to make x-rays is to focus an intense laser onto a gaseous-density target. The highly nonlinear but periodic motion discussed above will result in nonlinear scattering. For instance, when the strength of the light field approaches the Coulomb field binding electrons to nuclei, extremely high order harmonics can be observed, culminating in the recent observation of the 501st harmonic of 800-nanometer laser light. The mechanism responsible for this is scattering of the electron from the atomic nucleus. At larger light field strengths, the atoms become ionized, producing plasma, which disrupts phase matching and prevents the efficient generation of higher harmonics. In even larger fields, the electron will no longer even collide with the nucleus due to acceleration in the direction of the light wave. But when the field is increased yet further, the free electrons in the plasma begin to oscillate with relativistic velocities, and the nonlinear motion (discussed above) can produce harmonics. The usefulness of this nonlinearly Thomson scattered light, however, is limited, owing to the fact that the harmonics are scattered at large angles. Also, because the oscillation frequency is reduced, so too is the scattering efficiency into high harmonics.

Fortunately, at high laser intensities a directed beam of relativistic electrons is also produced in the direction of the laser light by laser-driven plasma waves. Lasers have been shown to accelerate greater than 10^{10} electrons to energies well above 1 MeV in low-divergence ($\lesssim 10°$ angle) beams at repetition rates of 10 Hz. The acceleration gradient is greater than 1 GeV/cm, 10^4 times greater than that of conventional radio-frequency accelerators. Recent experiments have shown that Compton scattering by such a co-propagating electron beam produces a collimated beam of high-order harmonics, also in the direction of the laser light (Figs. 2 and 3). Unlike Thomson scattering from low-velocity electrons, which produces only harmonics, Compton scattering from relativistic electron beams also results in a Doppler shift, which (in the case of counterpropagating beams) can further upshift the energy of the scattered light to the hard x-ray region of the spectrum. For example, electrons with only 100-MeV energy can boost a 1-eV energy photon to 50 keV. This opens up the possibility of an all-optically-driven "tabletop" hard x-ray source, which is of interest not only as a probe with atomic-scale spatial resolution but also as a medical diagnostic tool because of the large penetration of such energetic light through matter.

Fig. 2 Process whereby harmonic generation and a relativistic Doppler shift can upshift the frequency of visible radiation from a laser that Compton-scatters from an energetic electron beam to the x-ray region of the spectrum. Colliding a laser with 100-MeV-energy electron beams from a tabletop laser accelerator can produce 50-keV x-rays.

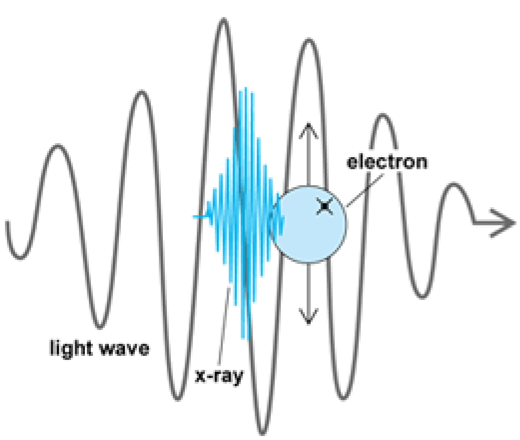
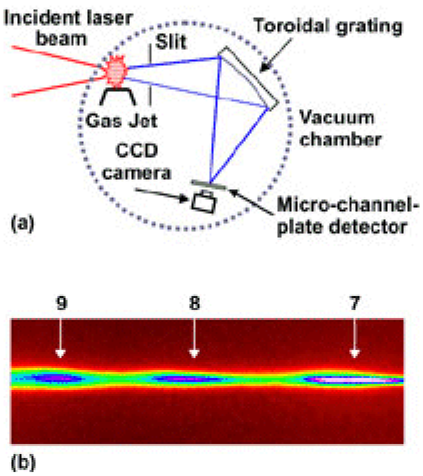


Fig. 3 Experimental study of nonlinear Compton scattering. (*a*) Apparatus. (*b*) Output of the charge-coupled-device (CCD) camera of the spectrometer, showing light at the 7th through 9th harmonics of the laser frequency.



Other x-ray sources

There exist other means to generate x-ray sources, such as synchrotrons and free-electron lasers. They rely on conventional (radio-frequency) accelerators to generate an electron beam, but because of their low field gradients (0.1 MeV/cm) they are usually quite large (tens to hundreds of meters in length). Long sets of magnets (tens of meters) are required to wiggle the electrons. Laser-Compton sources, by contrast, accelerate electrons in millimeter distances, and the electrons are wiggled in a millimeter-long interaction region by the magnetic field of the laser pulse. Consequently, laser-Compton sources will be much more affordable, thus potentially permitting their operation at university, industrial, and hospital laboratories. The latter will also provide better temporal resolution (femtoseconds instead of tens of picoseconds). There are proposals to build a short-pulse x-ray free-electron laser, but this will require a 50-GeV-energy electron beam conventionally accelerated in a 3-km-long (2-mi) tunnel to be passed through a 50-m-long (150-ft) set of wiggler magnets. Free-electron lasers do have the advantage over Compton sources that the electrons become tightly bunched, improving coherence and x-ray power.

Compton scattering has also been used to produce x-rays from electron beams that are conventionally accelerated. But besides being much larger, radio-frequency accelerators produce picosecond-duration electron bunches, which are mismatched with the femtosecond duration of the laser pulse, limiting their efficiency. This problem is mitigated with laser-accelerated electron beams, which can produce laser-synchronized femtosecond electron pulses.

Another laser-driven x-ray source is an x-ray laser, which is driven by electronic transitions in highly stripped ions. X-rays lasers do have the best coherence properties and are currently the brightest monochromatic sources in the extreme-ultraviolet region of the spectrum, but they do not scale to the hard x-ray regime. Although they produce shorter pulses than synchrotrons, their pulses, several picoseconds in duration, are still relatively long compared with laser-Compton sources.

Improved electron beams

One of the challenges for the future of laser-Compton x-ray sources is to find ways to produce more monoenergetic laser-driven electron beams in order to increase the number of scattered photons per unit bandwidth. A potential solution is optical injection of plasma electrons into laser-driven plasma waves. Higher-energy electron beams, gigaelectronvolts instead of megaelectronvolts, will dramatically increase the scattered power. A means to achieve this would be to increase the acceleration length by means of optical guiding of the intense light in preformed plasma channels or the use of multiple acceleration stages.

Applications

Laser-driven ultrafast x-rays can provide the requisite temporal resolution for the study of ultrafast processes such as conformational changes in ultrafast biology and chemistry, inner-shell electronic processes in atomic systems, and phase transitions in materials science. One problem they might help solve is the determination of protein structure. They are also useful in the study of photo-initiated processes, such as photosynthesis, because in this case the optical pump and x-ray probe are absolutely synchronized with each other, being derived from the same laser. Also, significant absorption of the x-ray probe pulse (such as occurs in the in vitro imaging of live biological cells) can destroy a sample or at least cause it to move. Thus, in order to acquire an image before the occurrence of blurring from this heat-induced motion, a single-shot pump-probe measurement with ultrashort-duration and high-peak-power x-rays is required. Low-repetition-rate, laser-produced x-ray sources are also best suited for studies of processes that are irreversible, and in which the sample must be moved between shots. Tunable x-rays that have energy near 50 keV can also be used in medicine for applications such as either differential absorption or phase-contrast imaging.

See also: Bremsstrahlung; Compton effect; Electron motion in vacuum; Laser; Nonlinear optics; Optical pulses; Particle accelerator; Plasma (physics); Scattering of electromagnetic radiation; Synchrotron radiation; X-ray tube

Donald Umstadter

BIBLIOGRAPHY

- F. Hartemann, *High-Field Electrodynamics*, CRC Press, Boca Raton, 2001
- G. A. Mourou, C. P. J. Barty, and M. D. Perry, Ultrahigh-intensity lasers: Physics of the extreme on a tabletop, *Phys. Today*, 51(1):22, January 1998
- D. Umstadter, Terawatt lasers produce faster electron acceleration, *Laser Focus World*, pp. 101-104, February 1996
- D. Umstadter, Physics and applications of relativistic plasmas driven by ultra-intense lasers, *Phys. Plasmas*, 8:1774-1785, 2001
- D. Umstadter and G. Mourou, Extreme light, *Sci. Amer.*, 286(5):81-86, May 2002

ADDITIONAL READING

- S. Banerjee et al., *High harmonic generation in relativistic laser-plasma interaction, Phys. Plasma*, 9:2393-2398, 2002
- S.-Y. Chen, A. Maksimchuk, and D. Umstadter, *Experimental observation of relativistic nonlinear Thomson scattering, Nature*, 396:653-655, 1998
- M. Hentschel et al., *Attosecond metrology, Nature*, 414:509-513, 2001
- Y. Salamin and F. M. H. Faisal, *Harmonic generation by superintense light scattering from relativistic electrons, Phys. Rev. A*, 54:4383-4395, 1996
- E. S. Sarachik and G. T. Schappert, *Classical theory of the scattering of intense laser radiation by free electrons, Phys. Rev. D*, 1:2738-2753, 1970
- D. Umstadter and T. Norris (eds.), *Nonlinear optics with free electrons, IEEE J. Quantum Electr.*, 33:1878, 1997

- High-field Science Laboratory at the University of Michigan Center for Ultrafast Optical Science

---

DOI 10.1036/1097-8542.030095
