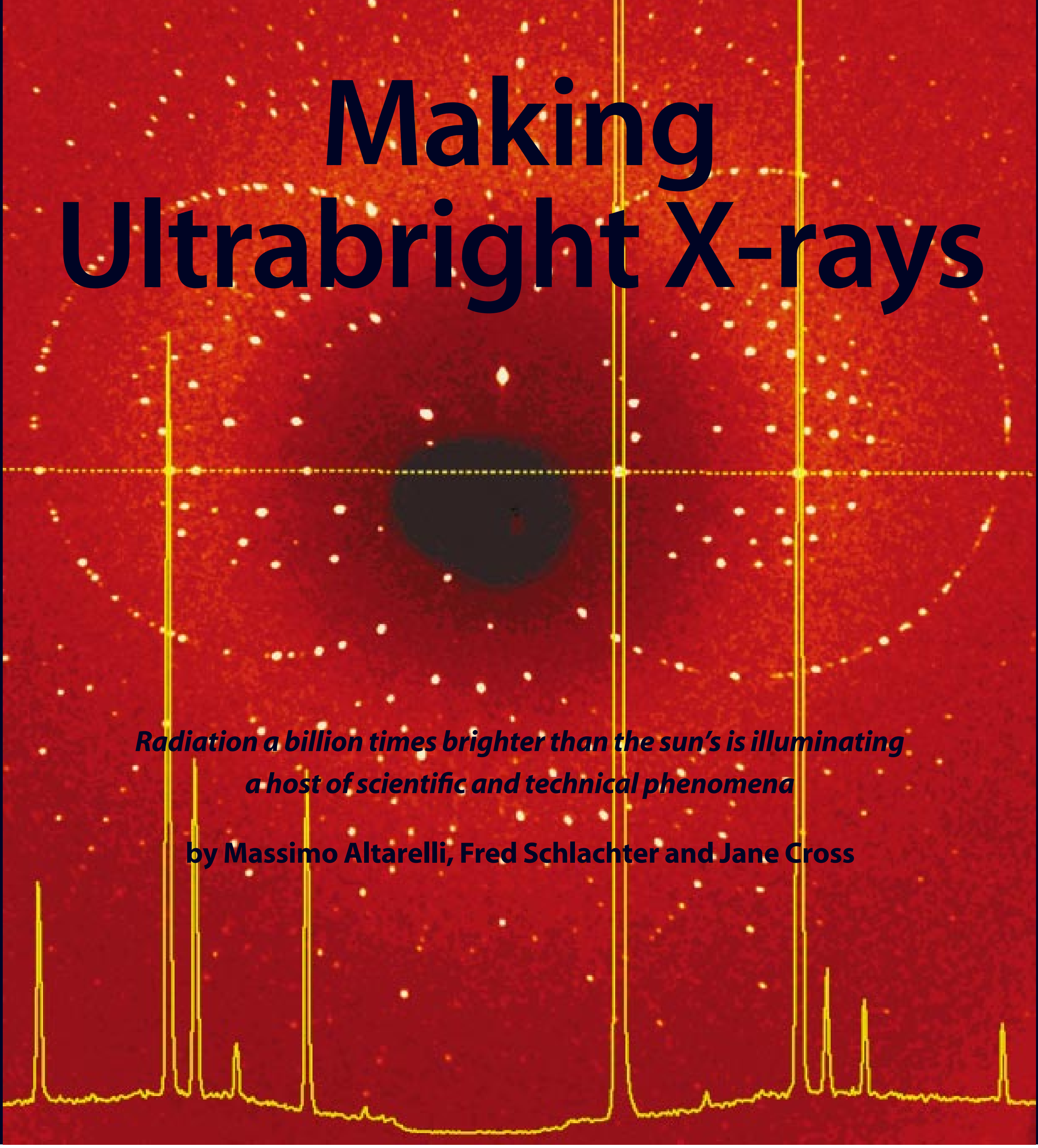
Making Ultrabright X-rays

Radiation a billion times brighter than the sun's is illuminating a host of scientific and technical phenomena

by Massimo Altarelli, Fred Schlachter and Jane Cross



DIFFRACTION IMAGE shows how a brief pulse of extremely bright x-radiation was scattered as it went through a sample of myoglobin, a molecule found in muscle tissue responsible for the uptake and storage of oxygen. This image shows both the spots of diffracted radiation and also a plot of the intensity of just those spots that lay along the horizontal line at the center of the pattern.

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The construction of extremely bright sources of x-rays has been one of the great—and infrequently told—success stories of science and technology over the past few decades. These facilities, based on evacuated, circular tubes several hundred meters in diameter, carry electrons at nearly the speed of light, giving off brilliant bursts of radiation that enable experimenters to examine matter on a scale measured in atoms. Using this extraordinary light, scientists have gained invaluable insights into diverse objects and phenomena, including the structure of molecules, advanced semiconductors and magnetic materials, and the details of complex chemical reactions.

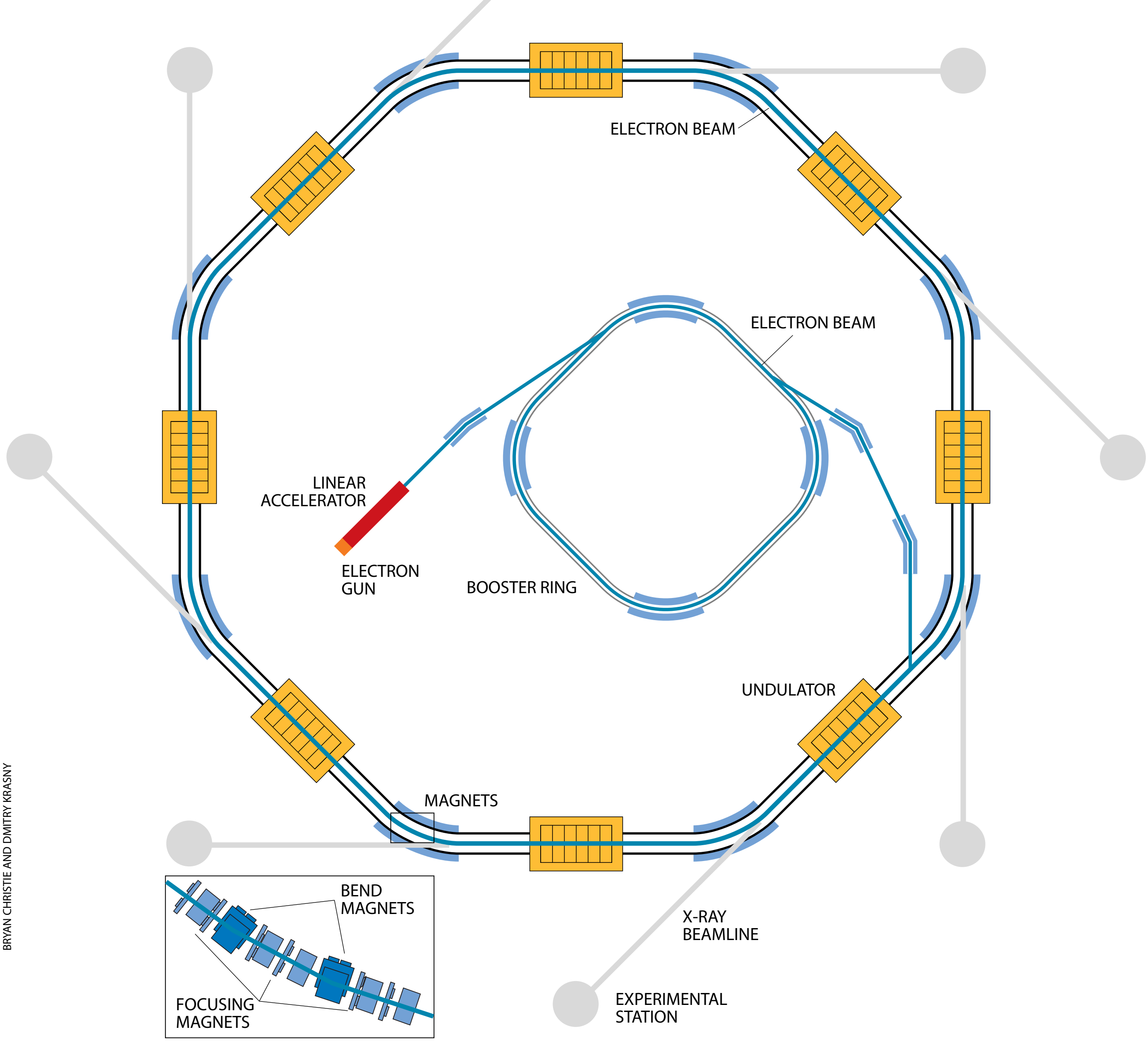
Such scientific achievements have been made possible by equally impressive engineering advances. Using the brightness of these x-ray sources as a yardstick, their rate of improvement since the early 1960s is matched by few other technologies. For example, the increase in computational speed available with the highest-performance computers is often cited as an example of the rapid pace of information-age progress. Yet the increase in brightness of the x-ray sources over the same period has occurred far faster.

The latest devices, examples of which have come on line over the past five years in various countries, are nearly 100 times brighter than anything built in the previous generation. In fact, these new sources are producing radiation a billion times brighter than that from the sun [*see box on page* 72]. Eight of these facilities are now operating, and another two are to begin operating in the near future [*see table on page* 69]. In addition, there are about 40 previous-generation sources operating around the world.

Fueling this surge in construction of new sources, despite price tags in the range of $100 million to $1 billion per site, is the promise of the most intimate look yet at the structure, composition and chemical bonding of crystals and molecules, in materials ranging from semiconductors to proteins.

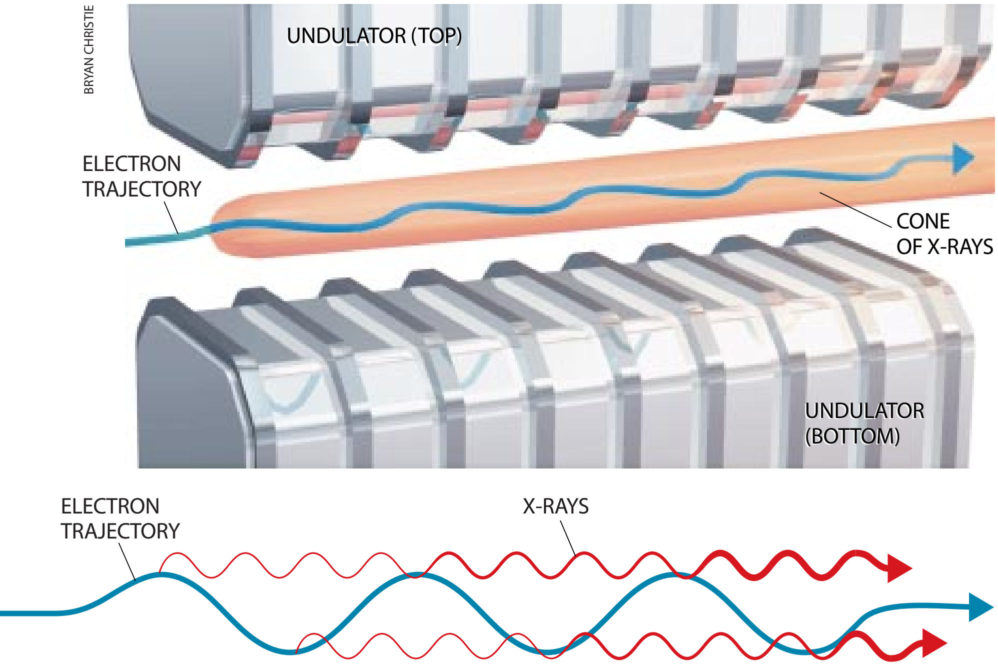
Succinctly put, the astounding brightness of these devices means that their x-rays come from a source with an extremely small cross-sectional area and that they shine in a very narrow cone. The x-rays come from electrons traveling in a bunch with a diameter about the same as that of a human hair. The x-ray beams those electrons emit also have a small cross section and low angular divergence, which allows the radiation to remain concentrated. To have high brightness, a beam must also have high spectral intensity, meaning that it is made up of an extraordinarily large number of photons per unit of time in a given range of wavelengths.

Brilliant x-ray beams are essential for many important classes of experiments, because in some situations the greater

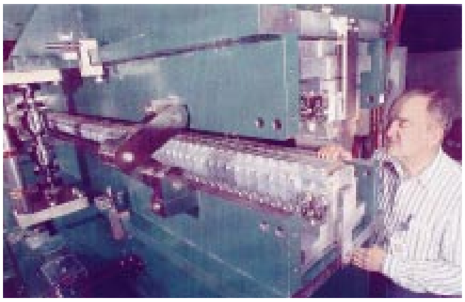


BRYAN CHRISTIE AND DMITRY KRASNY

STORAGE RING enables a current of electrons to circulate at nearly the speed of light for many hours. Electrons created in an electron gun are accelerated to nearly the speed of light by a linear accelerator. From there, they go into a small synchrotron, or booster ring, that increases the electrons' energy. Finally, the particles are injected into the storage ring, where they go around in hair-thin bunches, each of which causes a pulse of superbright electromagnetic radiation as it travels through any of the curved parts of the orbit. The main elements of the storage ring that control the circulating electron beam are magnets (*blue*) in an arrangement called a lattice. The focusing magnets (*detail at lower left*) keep the electrons in thin, concentrated bunches; the other magnets in the lattice bend the path of the electrons into a curve, causing radiation to be emitted. Radiation also comes from specially designed magnetic devices called undulators (*yellow*), which are installed in straight sections of the ring. Some of the radiation from the bend magnets, and most or all of the emissions from the undulators, leaves the ring through tangential ports into beamlines that allow the radiation to pass to experimental stations located around the ring (*gray circles*).



BRYAN CHRISTIE



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UNDULATOR creates a spatially alternating magnetic field that bends electrons back and forth many times to produce an x-ray beam of exceptional brightness. Waves from different points along the electron trajectory (*blue line*) overlap one another because x-rays are emitted in a narrow cone (*pink*). Only waves of certain frequencies overlap one another in such a way that all their peaks and troughs occur at the same positions—a condition known as constructive interference (*lower illustration at left*). These frequencies are determined by adjusting the size of the gap between the undulator's two rows of magnets (*above*).

the brightness, the smaller the objects that can be usefully probed. In addition, the brighter a source is, the narrower the range of wavelengths that can be selected in practice. Such fine selectivity is useful, for example, to excite a molecule that absorbs strongly at one resonant frequency.

Besides having desirable characteristics, the radiation from these facilities, which are more precisely known as storage rings, spans the wavelengths and energies needed to examine the atomic and electronic structure of matter. These two physical attributes determine nearly all of a material's key properties, such as its strength, magnetism and chemical reactivity, as well as its conduction of heat and electricity. The latest generation of x-ray sources is helping to advance our understanding of such important subjects as the malaria parasite, optical interferometry, catalysis and the manipulation of matter on an atomic scale.

Synchrotrons and Storage Rings

For roughly a century, scientists have known that charged particles give off electromagnetic radiation whenever they accelerate, decelerate or change direction. Thus, particles moving in a circle—even at constant speed—are accelerating and so emit radiation continuously as they follow the curved orbit. This radiation is known as synchrotron radiation because it was first observed about 50 years ago in an electron synchrotron, a kind of particle accelerator. Synchrotron radiation in fact occurs in nature, as in the Crab Nebula, which emits x-rays by the acceleration, in strong magnetic fields, of electrons whose speed approaches that of light.

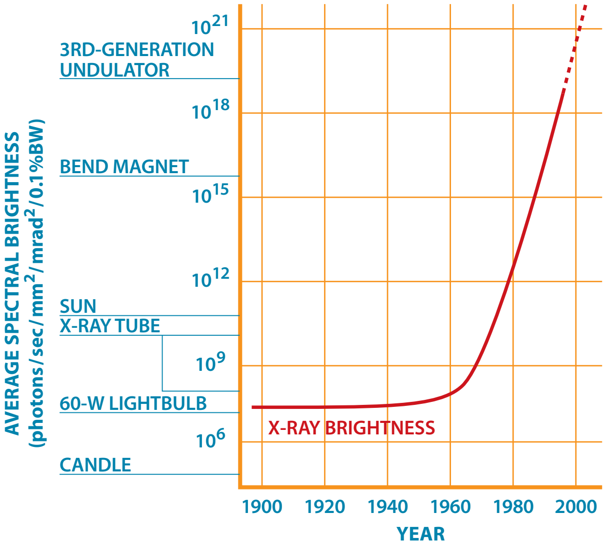
A synchrotron consists of a more or less doughnut-shaped vacuum chamber, which can be many kilometers in circumference, surrounded by magnets that bend and focus a beam of charged particles to keep them on the same path inside the vacuum chamber as they increase in energy. When the particles are circulating at speeds well below that of light, the radiation they emit is relatively weak, low frequency and omnidirectional. But as they approach the speed of light, the intensity, frequency and directionality of the emitted radiation increase dramatically. The radiation is emitted tangentially to the curving path of the particles. The emissions are particularly intense for particles that are not massive, such as electrons and positrons.

To create very bright beams of radiation for research, experimenters generally use storage rings, which are a specialized form of synchrotron. Storage rings circulate charged particles, typically electrons, at a constant speed—close to that of light—and in the same orbit for many hours. The particles must be brought to speed by a separate accelerator, often another synchrotron, before being injected into the storage ring. At the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, the electrons orbit at 99.999996 percent of the speed of light, a rate at which the effects described by Einstein's special relativity theory give each electron a mass some 3,000 times greater than what it is at rest.

As the swiftly moving electrons in a storage ring emit synchrotron radiation, they lose energy. For this reason, specially designed components known as radio-frequency cavities are needed to make up for such losses. These devices establish an oscillating electromagnetic field (a radio wave) that speeds the electrons on their journey.

The crest of each wave provides energy to a bunch of electrons. This phenomenon occurs once for each cycle of the radio wave—or 500 million times per second at the Advanced Light Source—for a duration of about 50 picoseconds (50×10^{-12} second). Traveling at nearly the speed of light, each hair-thin packet of electrons is roughly a centimeter in length, and there are hundreds of them in the storage ring at the same time, like tiny pearls in a huge rotating necklace. Each bunch produces an extremely short burst of x-radiation when it deviates from a straight line. Thus, storage rings produce extremely short, frequent and bright pulses of x-radiation.

A storage ring emits radiation that spans the electromagnetic spectrum from infrared to x-rays. In practice, however, physicists do not use the visible light given off, because tunable lasers are available that have even brighter beams at



DMITRY KRASNY

X-RAY BRIGHTNESS has increased dramatically since the first exploitation of radiation from particle accelerators (also known as synchrotron radiation) in the 1960s. Although all synchrotron facilities are significantly brighter than conventional x-ray sources, the newest machines, which use magnetic devices called undulators, generate x-ray beams that are about 100 times brighter than those from previous sources.

those wavelengths. But for the ultraviolet light and x-ray regions of the spectrum, no other practical source matches the brightness of synchrotron radiation.

Storage rings are actually polygonally shaped, with up to 50 straight sections connected by gently curved ones [*see illustration on page 67*]. Two types of powerful electromagnets focus the beam; a third type bends the path of the electrons into a curve, thereby causing synchrotron radiation.

In the curved sections, synchrotron radiation emerges tangentially to the electron beam. Thus, for each of the curved sections of a storage ring there is one or more associated x-ray "beam lines" that are used by experimenters.

Several factors have combined to permit the leap in brightness for the latest generation of storage rings. One is the availability of powerful, low-cost microprocessors. The design tools and control systems based on these microprocessors have now made it possible to design, model, construct and operate the myriad components and subsystems of a storage ring so exquisite control can be exerted over the electron beam. Operators can position this hair-thin beam to within a few hundredths of its width. Such extremely precise control keeps the beam very steady; movement of the electron beam would cause a blurred x-ray beam of lower brightness.

Another key factor has been the use of devices called undulators. As this name implies, an undulator causes the electron beam to bend back and forth many times over a length of a few meters. Recall that a change in direction—a form of acceleration—causes the electrons to emit radiation. An undulator, by forcing a series of rapid changes in direction in the electron beam, in effect squeezes out of it as much radiation as possible.

The waves of light emitted at each bend overlap and either reinforce or cancel one another, depending on their wavelengths [*see illustration on opposite page*]. The end result is that certain wavelengths are strongly enhanced. Light at these wavelengths emerges in a narrow cone and typically is partially coherent—that is, the crests and troughs of the waves tend to coincide with one another—making it similar in some respects to laser light.

The heart of an undulator is a double array of high-strength permanent magnets, which creates alternately upward- and downward-directed magnetic fields perpendicular to the electron beam. By adjusting the gap between the upper and lower magnets, researchers can tune an undulator so that all the emission falls near a specific fundamental frequency and its harmonics (multiples of that frequency).

Shining Future

The short wavelengths, extreme brightness and partial coherence of the x-ray beams from the latest storage rings are allowing researchers to investigate objects and phenomena that because of their size or other characteristics would have been difficult if not impossible to study as recently as five or six years ago. Hundreds of projects are under way, providing invaluable details on such disparate subjects as the performance of optical assemblies and the relation between the structure and the biological function of key proteins in the body.

Many of these experiments have potentially significant technological implications; others promise to elucidate long-standing scientific enigmas. The examples we have chosen illustrate how scientists and engineers are using these rings to investigate malaria parasites, to study technologies to reduce the size of transistors in future integrated circuits, to understand the way catalysis occurs on the surface of a material, to make images of the interior of minute samples without destroying them and to illuminate the dynamic behavior of the myoglobin molecule.

Among diseases caused by a single organism, malaria is a killer second only to tuberculosis. The World Health Organization estimates that every year malaria kills up to 2.7 million people, mainly children. There is no effective vaccine, and resistance to the available prophylactic drugs is growing. At Lawrence Berkeley National Laboratory's Life Sciences Division, Cathleen Magowan, collaborating with Werner Meyer-Ilse, John T. Brown and other members of the lab's Center for X-ray Optics, is using the Advanced Light Source to study the life cycle in red blood cells of the deadliest malaria parasite, *Plasmo-*

STATE-OF-THE-ART SYNCHROTRON LIGHT SOURCES

NAME	LOCATION	ELECTRON ENERGY*	DATE OF OPERATION
European Synchrotron Radiation Facility (ESRF)	Grenoble, France	6 GeV	1993
Advanced Light Source (ALS)	Berkeley, Calif., U.S.	1.5–1.9 GeV	1993
Synchrotron Radiation Research Center (SRRC)	Hsinchu, Taiwan	1.5 GeV	1994
Elettra	Trieste, Italy	2.0–2.4 GeV	1995
Pohang Light Source (PLS)	Pohang, Korea	2–2.5 GeV	1995
Advanced Photon Source (APS)	Argonne, Ill., U.S.	7 GeV	1996
MAX II	Lund, Sweden	1.5 GeV	1997
SPring-8	Nishi-Harima, Japan	8 GeV	1997
BESSY II	Berlin, Germany	0.9–1.9 GeV	1998
Swiss Light Source (SLS)	Villigen, Switzerland	2.4 GeV	2001

*The electron energy determines the range of photon energies produced by the light source; higher electron energies lead to higher photon energies.

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dium falciparum. This protozoan, which is carried by female *Anopheles* mosquitoes, invades the red blood cells of an infected host. Inside the host's cells, the parasites go through cycles of asexual division, insinuating their progeny into more and more red blood cells. Once inside a cell, the parasite digests hemoglobin in a food vacuole to produce most of the amino acids it needs to survive.

Magowan and her colleagues are using a transmission microscope in which an x-ray beam passes through infected red blood cells to make an enlarged image. They are studying various stages of the parasite's life cycle and viewing the effects of various drugs on it to see which are the most effective—and why. The researchers are using x-rays with a wavelength of 2.4 nanometers and get resolution five to 10 times better than would be possible with a visible-light microscope. In addition to the short wavelength of the illumination, the natural contrast from x-ray absorption lets the experimenters see minute structures within the infected cells and, in particular, inside the parasites themselves. This ability allows them to study the development of the parasite as it matures.

Moreover, the natural contrast from x-ray absorption allows precise and direct measurements of the redistribution of mass within the parasite, which is not possible with visible-light microscopes. Important examples of such features include abnormalities in the parasite's food vacuole, in which nutrients are accumulated. X-ray absorption provides the contrast that Magowan has used to follow redistribution of hemoglobin from the red-cell cytoplasm into the parasite food vacuole, both under normal conditions and under drug treatment. Drugs that inhibit parasite enzymes from digesting hemoglobin cause the food vacuole to swell with undigested hemoglobin and can thus kill the parasite. Magowan and her co-workers measured the increased mass in the parasite's food vacuole, which was not possible before on a microscopic scale. These x-ray studies, as well as others Magowan has done, could contribute to novel therapeutic approaches to the control of malaria.

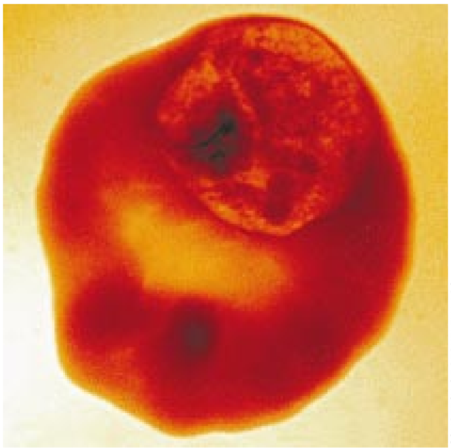
Bright, partially coherent x-ray beams may also aid the electronics industry. The core business of this industry, which generates hundreds of billions of dollars in revenue every year, is the manufacture of integrated circuits ("chips"). Chips are manufactured in a multistep process that creates and interconnects millions of transistors to form complex electronic systems on a sliver of silicon. The heart of the fabrication process is based on a cycle of photolithographic steps, in which ultraviolet light is used to project the image of a stencillike mask onto the photosensitive coating on a silicon wafer.

The wavelength of the light used in the exposure determines the minimum feature size that can be projected and therefore the density of transistors on the silicon. At present, features of 0.25 micron are produced using ultraviolet light with a wavelength of 0.248 micron. The industry, however, is already planning for chips with features measuring 0.1 micron or less. Currently one promising option to produce feature sizes smaller than about 0.1 micron uses photolithographic systems based on extreme ultraviolet (EUV) radiation. These EUV rays, with a wavelength of about 13 nanometers, will probably come from a laser-produced plasma.

Extreme Interferometry

Nevertheless, storage rings are playing an important role in the development of technologies for the manufacture of these extremely dense integrated circuits. EUV projection lithography will require the use of mirrors with multilayer coatings to focus the radiation (without such a coating, the mirrors would not sufficiently reflect EUV radiation that hits the mirrors' surface nearly perpendicularly). Achieving the necessary accuracy in the pattern projected onto the silicon wafer demands high precision in the optical system that projects the pattern and a very flat wafer surface. This kind of precision, in turn, requires methods of testing optical systems that can detect imperfections with dimensions of less than one nanometer (a thickness of just five to 10 atoms). Such a requirement would be difficult to meet with optical testing techniques that use visible light—which, in any case, could not test the multilayer coating.

At the ALS, however, researchers from the Center for X-ray Optics and the University of California at Berkeley's department of electrical engineering and computer science are developing a new method of measuring the performance of an optical system. The procedure uses EUV radiation from the storage ring and is based on interferometry, a sensitive optical technique in which information is obtained by the recombination of two or more coherent beams generated by the same source. Only radiation from a new-generation storage ring can provide a narrow, very intense beam at the EUV wavelengths that are necessary for this application.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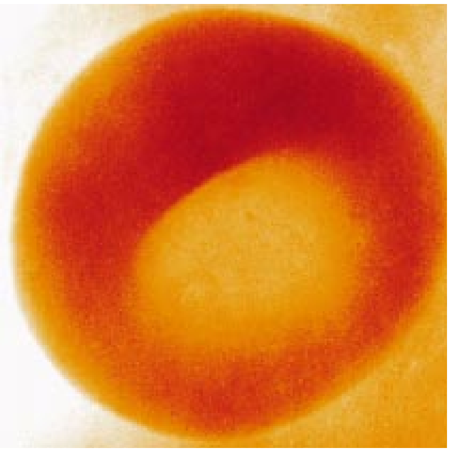
MALARIA PARASITE is visible in unusual detail in this x-ray image (*above*) of an infected human red blood cell. The photograph at the right shows a healthy cell imaged using the same technique.

With interferometry, the beams propagate along different paths, or in different ways. One beam interacts with an object under study, shifting the phase of the waves in that beam. (A 180-degree phase shift, for example, would leave the crests where the troughs were, and vice versa.) The other beam, meanwhile, serves as a reference.

When the two beams are brought together, or recombined, any relative shift in phase—due to aberrations in the optics being tested—becomes apparent as a pattern of light and dark fringes where the waves are constructively or destructively interfering. Following this approach, the group of investigators, headed by Jeffrey Bokor, built an interferometer that divides coherent light from an undulator source into two beams. One is reflected through the optical system under test, acquiring phase information that reveals the quality of the optical system. The second beam radiates through a tiny pinhole, producing a spherical reference beam. The group's work with ultraviolet light has demonstrated the ability to fabricate mirrors of sufficient accuracy for projection lithography at EUV wavelengths. In so doing, these researchers surmounted a major challenge to packing more transistors into microcircuits.



Bright synchrotron radiation is also furthering our understanding of how atoms and molecules interact (bond) with a surface—and how their electronic structure changes as a result of that interaction. This insight is important in the study of corrosion and also of catalysis, in which two chemical agents are induced to react by the presence of a third. Both phenomena are of enormous practical significance; catalysis, for example, is used in industry to produce many different compounds.

Neither phenomenon can be well understood without a clear picture of how atoms or molecules bond to a surface. To study this subject, scientists need a probe that can see how the electrons that form a chemical bond are distributed on each of the atoms involved in the bond. Such an "atom-specific" view is now possible using a high-brightness source and a technique called x-ray fluorescence spectroscopy.

A research group working at the ALS led by Anders Nilsson and Nial Wassdahl of Uppsala University in Sweden, in collaboration with the IBM Almaden Research Center, was one of the first to demonstrate this capability. This study of the chemical bond between molecular nitrogen (N_2) and a nickel surface has revolutionized our conception of the surface bond.

The nitrogen molecule is known to "stand up" on the nickel surface rather than to lie flat. In other words, only one of the nitrogen atoms in the molecular pair bonds to the surface; the other nitrogen atom sticks up from it. Because the bond to the surface is much weaker than the internal bond between the nitrogen atoms, chemists had assumed that the presence of the surface hardly affects the molecule and that it could therefore be treated as a symmetrical unit of two essentially identical nitrogen atoms. Yet what the researchers found was that there are large changes in the nitrogen's electron orbitals on adsorption, leading to a very different local electronic structure for each of the two atoms and a weakening of the intramolecular (N-N) bond. Understanding how and why the dissociation takes place could be a key to increasing the efficiency of ammonia synthesis for fertilizer and other nitrogen-containing molecules, because the rate-limiting step in the current process is the dissociation of N_2 into two separate nitrogen atoms.

Using the ALS, the researchers probed the energy-level differences in the inner-shell electrons of the two nitrogen atoms (a difference in energy level means a difference in the energy required to remove an electron from the atom or molecule). By tuning the energy of the incoming photons, the experimenters could selectively excite electrons from one nitrogen atom or the other and not those from the nickel surface on which the molecule was adsorbed. Information about the structure of the atom's outer electron layers was contained in the fluorescence x-rays emitted as the excited atoms returned to their ground state.

The experiment required a high-intensity source because x-ray fluorescence spectroscopy yields only about one photon emitted per 1,000 photons absorbed. And it required the ability to produce x-rays in a very narrow spectrum to selectively excite only one nitrogen atom of the two in the N_2 molecule.

Seeing through a Mosquito's Knee

Another potentially important application of high-brightness beams is phase-contrast imaging, which was recently demonstrated for the first time with high-energy x-rays by Anatoly Snigirev and his co-workers at the European Synchrotron Radiation Facility (ESRF). Their achievement opens the way to nondestructive imaging of biological, mineralogical and certain metallurgical samples at micron resolution. For example, Snigirev's group recently used the technique to make stunning x-ray cross-sectional images of a mosquito's knee [*see illustration on page 73*].

X-ray imaging is normally based on absorption contrast, as in the familiar medical imaging. In this case, contrast, which distinguishes different constituents of the object under examination, exists in the image because certain materials (those composed chiefly of elements with low atomic numbers, such as carbon, nitrogen and oxygen) are more transparent to x-rays than others.

In general, items composed of heavier atoms, which have a higher density of electrons, are more likely to absorb x-rays. In a conventional medical x-ray image, for example, bones stand out because they project a more pronounced shadow on the film than the less dense tissue surrounding them. Absorption contrast, therefore, is not well suited for samples that are composed exclusively of atoms of low atomic number.

Phase-contrast imaging relies on a different effect. Instead of the variation in absorption, it uses the variations in refractive indexes of the different substances within the sample. The refractive index of a material determines the deviation in the direction of a ray as it enters the material. For x-rays, differences in refractive indexes between different media are very small, at most one part in 100,000, but they are big enough to be exploited for imaging.

The basic principle of phase-contrast imaging with short-wavelength x-rays is identical to that of in-line holography. A coherent beam from a very bright source passes through a low-density specimen. Segments of the x-ray wavefront are deflected to a different degree relating to small variations in indexes of refraction. Consider first what happens near the edges of the sample: the rays that pass just by the sample are undeflected, but those that go through it are slightly deflected and get a bit out of step with respect to the undeflected ones. At some distance behind the sample, the various sets of wavefronts superimpose and, because they originate from a coherent beam, interfere. Thus, the characteristic fringes in intensity of an interference pattern are set up. These fringes, when recorded on a detector, map the outer contour of the sample. The same kind of interference takes place at the internal interfaces between regions of the sample that have different indexes of refraction. An exciting feature of the technique is that it is possible to make tomographic "cuts" through the sample, similar to those of a medical CT scan, by reconstructing a series of images made as the sample is rotated to expose it from different angles.

Bright x-ray beams are also illuminating long-standing scientific mysteries, including the nanosecond-by-nanosecond behavior of biologically important molecules such as proteins. Biology researchers and the pharmaceutical industry are putting an ever increasing demand on light sources, given the significance of proteins for the understanding of life and of disease and for the development of new drugs. Protein molecules (which include enzymes, hormones and antibodies) are fundamental building blocks of living beings.

The effort to elucidate the behavior of protein molecules hinges on a technique called macromolecular crystallography, an important application of synchrotron radiation that enables researchers to map out the many thousands of atoms that make up large biological molecules such as proteins and viruses.

Basically, the information obtained in these studies is a static picture or "snapshot" of the atomic positions in the large molecules. But proteins are not at all static and rigid; they undergo complex structural rearrangements while carrying out their biological function. Today measuring and understanding these changes is largely unexplored territory, but there are clear indications that the new high-brightness facilities will allow progress in this direction.

For example, Michael Wulff of the ESRF, in collaboration with Keith Moffatt of the University of Chicago and others, has been able to follow the rapid structural rearrangements of myoglobin, a protein found in muscle tissue that is responsible for the uptake and storage of oxygen. Their work has resulted in a kind of movie, with each frame captured by a nanosecond-long x-ray pulse, which depicts the changes in the myoglobin molecule over a period of about one millisecond. The researchers are trying to discover the specific structural changes that allow an oxygen molecule to enter or leave a cagelike enclosure within the myoglobin molecule.

The intensity of current-generation light sources is such that a single pulse contains enough photons to take an x-ray "picture" (actually, a diffraction pattern) sufficient to reconstruct the configuration of the protein. To follow the structural rearrangements of the myoglobin protein during the release and rebinding of carbon monoxide, a sophisticated electronic setup controls the arrival of a laser pulse that lasts less than a nanosecond. This pulse breaks the chemical bond between the oxygen molecule and the heme site, which is the

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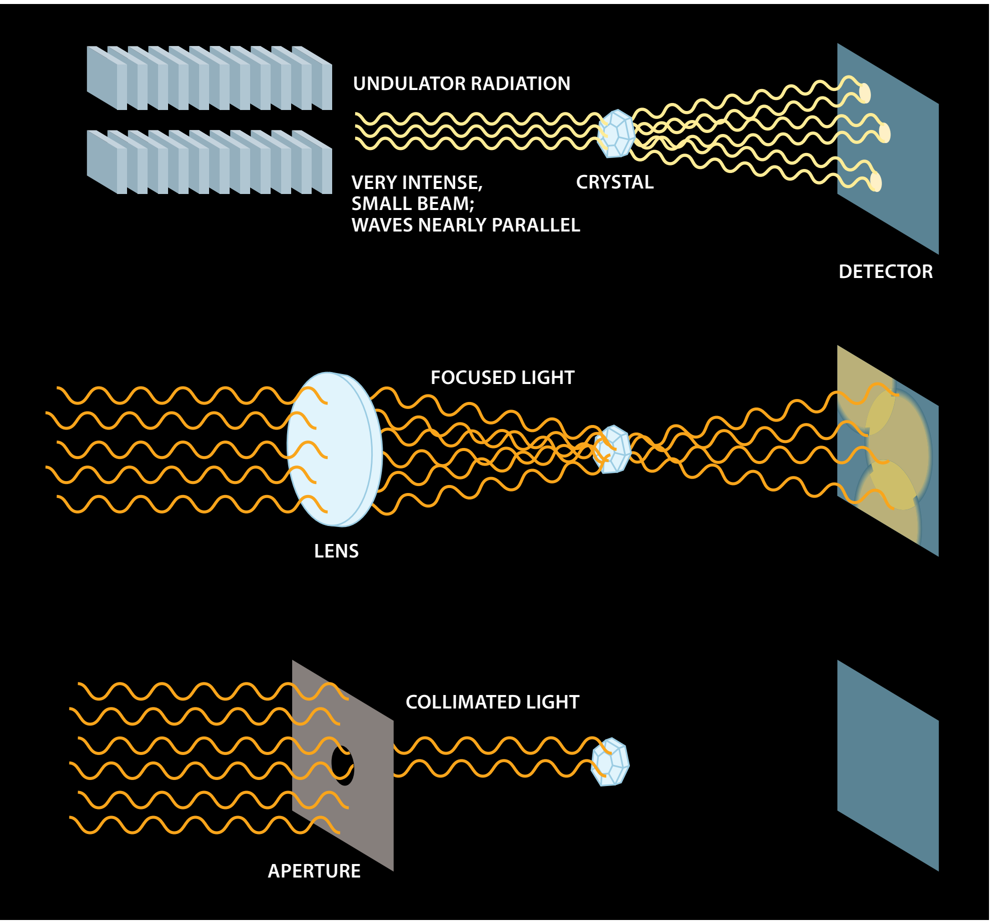
Brighter than the Brightest Star

Brightness is not simply the intensity of light but rather a measure of the degree of concentration of the light into a small emitting area and angle. Two sources may radiate the same amount of light, but the one in which the light comes from a small area and is collimated, meaning it shines in a narrow cone, is the brighter of the two. Thus, not only is a laser typically brighter than a lightbulb, but it can even be considerably brighter than the sun, which is large and radiates light equally in all directions.

Besides a source of small dimensions and a high degree of collimation, high brightness also demands high spectral flux, a technical term for the emission of many photons per second in a given range of wavelengths. A bright beam is also at least partially coherent, meaning that two separated but simultaneous waves can interfere with each other; this property is important for many scientific applications.

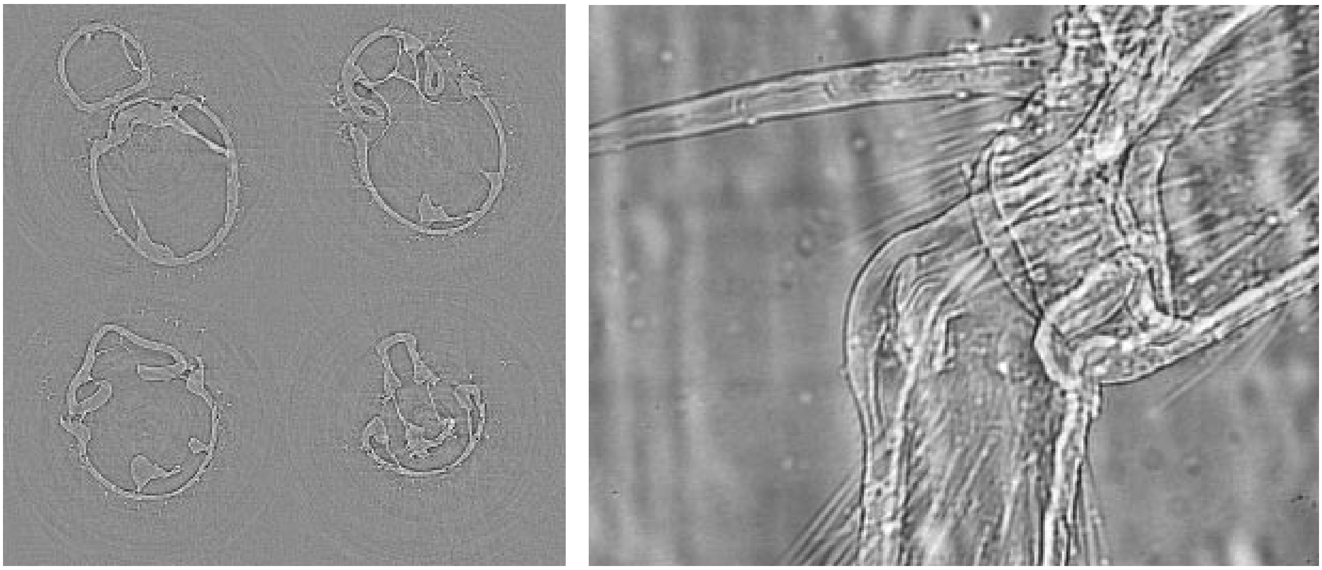
Brightness, called brilliance by European scientists, is an intrinsic property of a light source. It might seem plausible to increase brightness by focusing a beam to a small spot using a lens or a curved mirror. Yet by so doing, you would be increasing the divergence of the beam (making it less collimated)—and therefore not improving its brightness. Alternatively, you could decrease spot size without increasing angular divergence by using a tiny aperture; however, such a scheme would reduce the flux (the number of photons per second) on the sample and thus would not increase brightness either.

—M.A., F.S. and J.C.



DMITRY KRASNY

BRIGHTNESS of a beam cannot be improved. When a bright beam from, say, an undulator falls on a crystal, it creates a pattern of sharp, distinct diffraction spots (*top*). A lens may be used to focus a less bright beam (*middle*); however, this strategy trades beam size for divergence. The photons converge on the crystal and then diverge behind it, resulting in large, overlapping diffraction spots that contain much less information about the crystal. (In general, the beam can be magnified or demagnified, but the product of its cross-sectional size and the angle of divergence in each plane are constant.) An aperture can be used to make a smaller beam without increasing divergence (*bottom*). The problem in this case is dimness; the resulting diffraction spots are hard to detect and thus reveal little data.



MOSQUITO'S KNEE, imaged by a phase-contrast x-ray microscope, reveals anatomical detail on the scale of a few microns—despite the absence of any material as dense as the bones of vertebrates. Tomographic views of various cross sections of the mosquito knee were reconstructed by computer from images taken at different angles (*left*).

ANATOLY SNIGIREV *European Synchrotron Radiation Facility*

iron-containing part of the myoglobin molecule. In the experiments the researcher substituted carbon monoxide for oxygen, because CO has a higher probability of being detached from the heme site when it absorbs a laser photon.

After the laser pulse triggered the photochemical release of the CO from the myoglobin, there was a short interval before the x-ray snapshot was made. The researchers repeated the experiment many times, in each case with a slightly longer time interval between the laser pulse and the x-ray snapshot. By putting together all the snapshots, the investigators made a movie of structural changes on a nanosecond-by-nanosecond timescale. The movie showed that a few nanoseconds after the start of the reaction, the CO molecule is four angstroms away from the iron atom, which sits at the center of the iron-containing part of a myoglobin molecule and to which it was originally bound. Furthermore, at that instant the CO is rotated by 90 degrees with respect to its original orientation. In this "hold" position, the CO can wait hundreds of nanoseconds for a configuration of the environment that allows it to leave the protein and become available for participation in the chemical reactions that provide the energy necessary for muscle contraction.

Most important, researchers have for the first time been literally able to watch the time behavior of a dynamic molecular-biological process. This achievement opens the way to an understanding—in atomic detail—of the kinetics and dynamics of other important reactions involving proteins.

Such uses are just a few of the ones that are collectively advancing and in some cases even revolutionizing entire fields of technology and science. In time, such achievements will lead to demand for a yet more advanced generation of light sources. These ultrabright sources may be based on free-electron lasers, which are built around very long and complex undulators. (In these undulators, photons generated upstream react further downstream with electron pulses. This reaction reinforces the emission of more photons in step with the ones emitted upstream.)

This technology will yield beams many orders of magnitude brighter than those from today's storage rings, sustaining the remarkable rate of advancement in this area. More important, these future facilities will deepen our understanding of increasingly complex systems, extending the set of phenomena illuminated by this extraordinary light. SA

The Authors

MASSIMO ALTARELLI, FRED SCHLACHTER and JANE CROSS share an interest in describing the results achieved at large, government-funded research facilities to the general public. Altarelli is the newly appointed director of the Elettra light source in Trieste, Italy. He is leaving the European Synchrotron Radiation Facility in Grenoble, France, where he was head of the theoretical physics group and, prior to that, scientific director for physics and materials science. His research activity has been concerned with the investigation of magnetism and phase transitions by x-ray scattering and absorption. Schlachter joined the staff of the Advanced Light Source in 1989, while it was being constructed, and has held a number of positions there. His current interests include quantum chaos as it is exhibited by atoms in highly excited states. Cross is a writer, editor and former science teacher whose numerous technical and scientific publications span a variety of subjects. From 1993 until 1997, she worked as a scientific communications specialist at Lawrence Berkeley National Laboratory.

Further Reading

SYNCHROTRON RADIATION. Herman Winick in *Scientific American,* Vol. 257, No. 5, pages 88–99; November 1987.

X-RAY MICROSCOPES. Malcolm R. Howells, Janos Kirz and David Sayre in *Scientific American,* Vol. 264, No. 2, pages 88–94; February 1991.

Information on light sources around the world is available on the World Wide Web sites of the Advanced Light Source and the European Synchrotron Radiation Facility: www-als.lbl.gov and www.esrf.fr, respectively. The ALS also maintains an interactive site for exploring the structure of materials. The site, which is oriented to teachers and high school students, can be reached at www.lbl.gov/MicroWorlds