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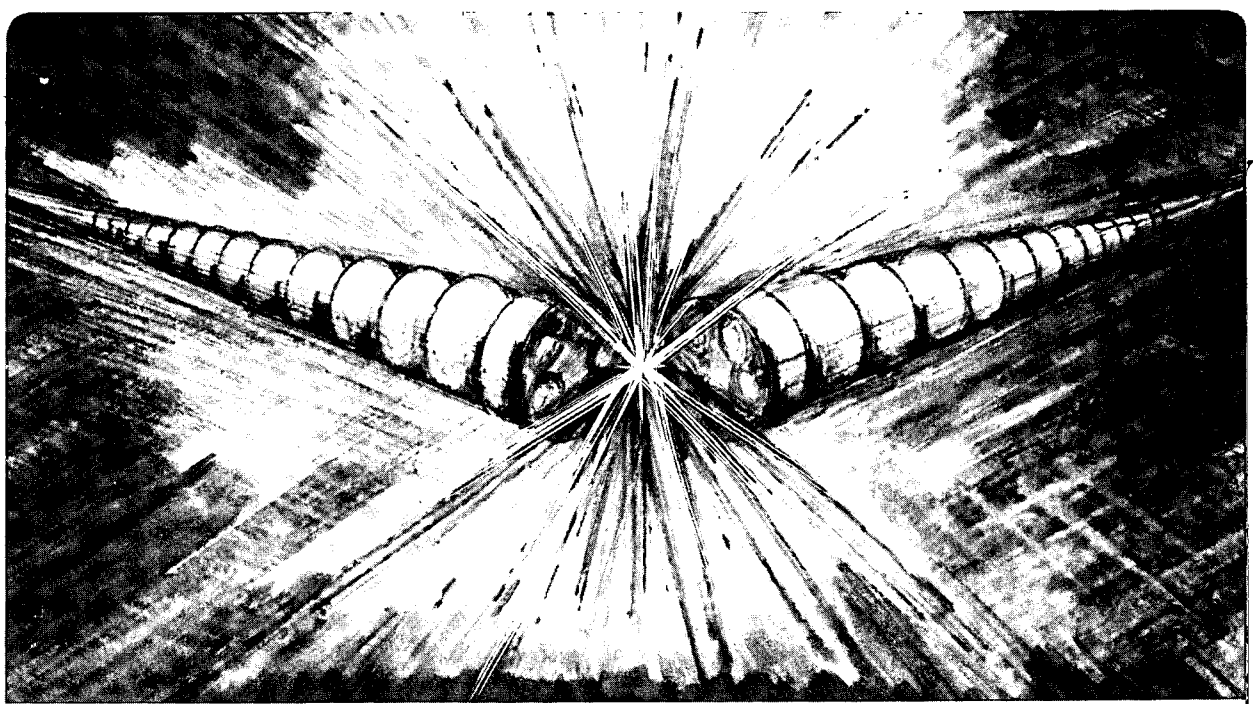

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Third-generation synchrotron sources: x rays of unprecedented brightness for scientific and industrial applications

Dr. Arthur L. Robertson and Dr. Alfred S. Schlachter

Since their discovery by Wilhelm Roentgen in 1895, x rays have provided scientists with a unique tool for examining the structure, composition, chemical bonding, and other properties of matter ranging from semiconductor chips to proteins and similar biological macromolecules. The brightest x-ray sources readily usable for this type of research are electron accelerators known as storage rings, which emit beams of synchrotron radiation far more intense than the radiation produced by the x-ray tubes found in laboratories and hospitals. Beginning in 1993, the first of a new generation of facilities—so-called third-generation synchrotron-radiation sources—came into operation and began producing vastly brighter beams of x rays than ever before.

Brightness (which, along with flux, is one of the two basic parameters that measure the performance of a source) is the key feature of third-generation synchrotron sources. Flux is the number of photons generated per second. Two sources may have the same flux but vary vastly in brightness: a small, laser-like source emitting a narrow cone of radiation is much brighter than a large source, such as a light bulb, emitting in all directions with the same flux. The advantages of brightness are well illustrated by the revolutionary impact the needle-thin beams of lasers have had on visible and infrared spectroscopy in the last 30 years.

Third-generation synchrotron sources are in many ways like x-ray lasers. At the forefront of research, the ability to concentrate a large number of x rays at a specific wavelength onto a small sample area is the difference between doing and not doing an experiment. Consequently, more than 20 such facilities around the world are being planned, are under construction, or are already operating. Two of these are in the United States. The Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory, when it was completed in the spring of 1993, became the first American third-generation synchrotron source to begin operation (see figure 1). The Advanced Photon Source (APS) at the Argonne National Laboratory is a sister facility with complementary capabilities, now under construction with a projected start-up in the fall of 1995.

Synchrotron radiation is generated by electrically charged particles following a curved trajectory. The wavelength range of the spectrum produced depends on the particle energy, its rest mass, and the radius of curvature of its path. High energy, low mass, and small radius of curvature all extend the spectrum to shorter wavelengths. The term *synchrotron radiation* derives from the particle accelerators known as synchrotrons. In these machines, magnetic fields deflect electrons into a curved trajectory while the electrons are being accelerated to high energy.

Several features of synchrotron radiation motivated the initial interest in it as a source of light for scientific research. First, for relativistic electrons traveling at nearly the speed of light, the synchrotron radiation spectrum is broad, continuous, and most intense at ultraviolet and x-ray wavelengths. Second, relativistic effects compress the radiation into a narrow forward cone tangential to the electron path. Finally, the pulsed nature of the beam in high-energy accelerators also means that synchrotron radiation is pulsed. This combination of a continuous spectrum, high intensity, collimated beam, and pulsed time structure is not available from conventional ultraviolet and x-ray sources.

First observed experimentally in 1947 from a tiny electron synchrotron at General Electric's R&D center in Schenectady, New York, synchrotron radiation has evolved rapidly to the current third-generation facilities geared toward scientific and technical research using synchrotron light. The first generation comprises electron accelerators designed and operated for high-energy physics, which provide synchrotron radiation as a by-product. The second generation comprises dedicated synchrotron sources built around electron storage rings in which the electrons circulate for many hours at constant energy, thereby providing stable, reliable sources that operate for the convenience of synchrotron users. These machines were also designed to increase the brightness over that available from first-generation high-energy physics machines.

Second-generation storage-ring designers increased the brightness by decreasing the emittance of the electron beam. The emittance is a composite parameter that measures the electron beam size and divergence, quantifying how far away the electrons in the beam are from the positions and directions of travel they would have in an ideal orbit. Since the electron beam is the radiation source and the radiation is emitted tangential to the electron path, reducing the emittance increases the brightness in two ways: bringing electrons' positions closer to the ideal orbit reduces the source size of the beam, and bringing electrons' angles of travel closer to the ideal reduces the opening angle of the emitted radiation cone. The emittance is determined by the number, strength, and arrangement of magnets (dipoles, quadrupoles, and sextupoles) that guide and focus the electron beam in the curved arcs of the storage ring.

A further increase in brightness can be obtained by using special magnetic structures called undulators that fit in the otherwise empty straight sections of a storage ring, between the curved arcs. The use of undulators and similar devices, along with still lower emittance than second-generation sources (by a factor of 10 or so), characterize the third generation of synchrotron radiation sources, although second-generation sources have also been retrofitted with undulators. Third-generation sources have long straight sections for undulators, since brightness scales with undulator length. The most common undulator (see figure 2) bends the electrons into a roughly sinusoidal trajectory in the horizontal plane of the electron-beam orbit. Each magnetic pole in the undulator acts as a source of synchrotron radiation that adds coherently with its neighbors to increase the brightness dramatically. In the ALS, for example, the brightness of undulator radiation is about 10,000 times that of bend-magnet radiation (see figure 3).

The brightness of undulator radiation arises from three factors. First, the magnetic structure includes a large number of poles, each of which adds to the brightness. Second, the broad spectrum of bend-magnet radiation is compressed into a highly peaked spectrum comprising a fundamental and several harmonics, so the flux in a narrow wavelength range can be much higher. Third, the radiation cone is more narrow than that of bend-magnet radiation. Although the wavelengths of the fundamental and its harmonics can be tuned by varying the undulator magnetic field, the tuning range is narrower than the bend-magnet spectrum, and it is difficult for a single synchrotron radiation facility to cover effectively the entire wavelength range from the ultraviolet through the x-ray with undulators. Consequently, the third-generation facilities specialize in producing either short-wavelength x rays (also known as hard x rays) or long-wavelength (soft) x-rays and ultraviolet.

The undulator spectrum shifts to shorter wavelengths as the electron energy increases. For this reason, the storage rings required for hard x-ray facilities tend to be considerably larger and more expensive than those specializing in soft x-rays and ultraviolet. In the United States, the APS with a beam energy of 7 billion electron volts (GeV), circumference of 1,104 meters (3622 feet), 42 straight sections, and total cost of $812 million is the hard x-ray source, while the ALS with a beam energy of 1.5 GeV, circumference of 197 meters (646 feet), 12 straight sections, and total cost of $146 million is the soft x-ray source.

The payoff from this heavy investment in new facilities is expected to be comparably impressive, if difficult to predict in detail, across a broad swath from quite basic research in atomic physics to such industrial applications as analyzing semiconductor wafers for trace impurities. In fact, industry is expected to be a prime beneficiary of third-generation sources. Three examples:

• The pharmaceuticals market is $150 billion per year worldwide, but most drugs on the market today were discovered by trial and error. To make drug development more efficient, many companies are turning to "structure-based" drug design—an approach that begins with detailed information about the positions of the atoms in a molecule known to play a role in a disease. The method of determining the structure is called protein crystallography, and it requires intense beams of highly collimated x-rays.

• The race for dominance in making chips to drive computers—a worldwide market worth more than $80 billion per year—will be won by companies that can cram the most circuitry into the smallest area for the least cost. To further shrink the size of circuit features and the spaces between them, manufacturers are investigating the use of extreme ultraviolet (EUV) projection lithography in which EUV light shines through a stencil-like mask and lenses to start the process of etching circuits onto silicon wafers. EUV light from undulators will be used to develop mirrors and lenses needed for this technology.

• Motors that can pass through the eye of needle or tweezers that can grasp a single-celled organism are today being manufactured commercially. The present market for

these microscopic and parts is estimated at $500 million per year, but it has the potential to jump to $10 billion by the turn of the century. Known as micro electro-mechanical machines (MEMS), many of these devices will be manufactured by a new technique called deep-etch x-ray lithography, using synchrotron radiation.

Although medical images, which measure only the intensity of x rays transmitted through different parts of a sample, are what first comes to mind in thinking of x rays, there is actually a wealth of techniques for translating the response of a sample to illumination with an x-ray beam to information about structure, composition, chemical bonding, and other properties. The response may also be a change in the direction of the x rays, the emission of x rays of a longer wavelength, the emission of electrons from the surface, or the emission of ions from the surface. The most common experimental techniques, each of which may have several variants, include x-ray diffraction, x-ray absorption spectroscopy, x-ray emission or fluorescence spectroscopy, photoelectron spectroscopy, photoion spectroscopy, and desorption spectroscopy. The pulsed nature of synchrotron radiation also makes it possible to monitor time-dependent processes on time scales as short as 100 picoseconds (one ten-billionth of a second).

The single most exciting advance made practical by high brightness is the addition of spatial resolution to the various spectroscopic techniques already in existence. Collectively, these techniques are called spatially resolved spectroscopy or spectromicroscopy. In traditional experiments, the x-ray beam illuminates a comparatively broad area—50 micrometers (0.002 inches) or more in diameter at the ALS—of the sample surface, which more often than not is inhomogeneous in structure, composition, chemical bonding, and other properties on a much smaller distance scale. The measured signal therefore contains a mixture of information about the various regions illuminated.

To obtain spatial resolution, scientists can use either scanning or imaging methods. In the first case, x-ray lenses focus the beam to a small spot illuminating the area of interest; the spot can then be scanned across the surface to build up an image. In the second, a large area is illuminated, but optical or electromagnetic lenses preserve the spatial relationship of the photons or electrons that constitute the signal until they reach a position-sensitive detector. The third-generation sources based on undulators will turn these spatially resolving techniques from cumbersome demonstration experiments into accessible tools for the investigation of complex, real-world systems. Depending on the technique used and the information desired, the spatial resolution may be as small as 5 nanometers (two ten-millionths of an inch).

As it happens, surface areas of the order of 1 to 10 square nanometers (1.5 to 15 quadrillionths of a square inch) mark the frontier for many technologies, from microelectronic circuitry to magnetic storage devices to catalysts for chemical reactions. Catalysts, for example, promote the efficiency and selectivity of chemical reactions, so that the maximum quantity of desired product results. An overwhelming number of chemical production processes, including the refining of fuels, involve catalysts in at least one step. Many of the catalysts used in industry consist of small metal particles,

ranging in size from 1 to 100 nanometers (40 to 4000 billionths of an inch), supported on a microporous oxide with a very high surface area. To improve catalysts further, it is necessary to understand the catalyst structure and behavior at the individual particle level, a task well matched to spectromicroscopy with a third-generation synchrotron source.

Other techniques that will emerge as forefront techniques at the third-generation synchrotron sources include soft x-ray fluorescence spectroscopy and x-ray magnetic circular dichroism spectroscopy. Soft x-ray fluorescence—the emission of a long-wavelength x ray following x-ray absorption— is an important method of studying structures located well below the sample surface, such as the interface between a coating and the substrate it covers. So-called buried interfaces are widespread in technologically important materials. Circularly polarized x rays are essential for studying the structure of magnetic materials, such as those used for computer disks, as well as molecules whose physical structure has a "handedness," such as the helical biomolecules.

In sum, third-generation synchrotron radiation sources stand poised to make major contributions to both basic research and technology development in almost every domain where x rays serve as a useful tool.

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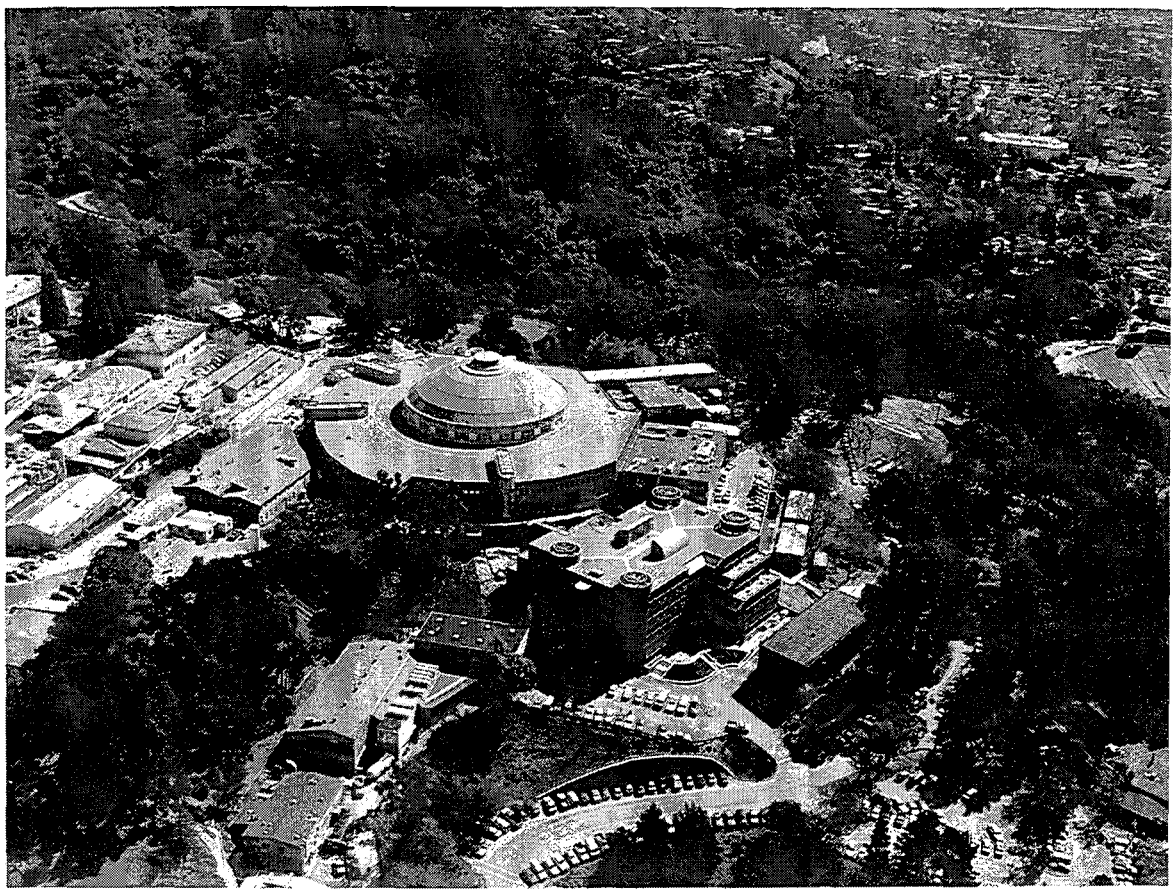

Fig. 1. The Advanced Light Source (ALS) at Lawrence Berkeley Laboratory is the first third-generation synchrotron radiation facility in the United States. Both the ALS and the Advanced Photon Source at Argonne National Laboratory are U.S. Department of Energy national user facilities and are open to scientists from industrial, academic, and government laboratories. [Photo courtesy of the Lawrence Berkeley Laboratory]

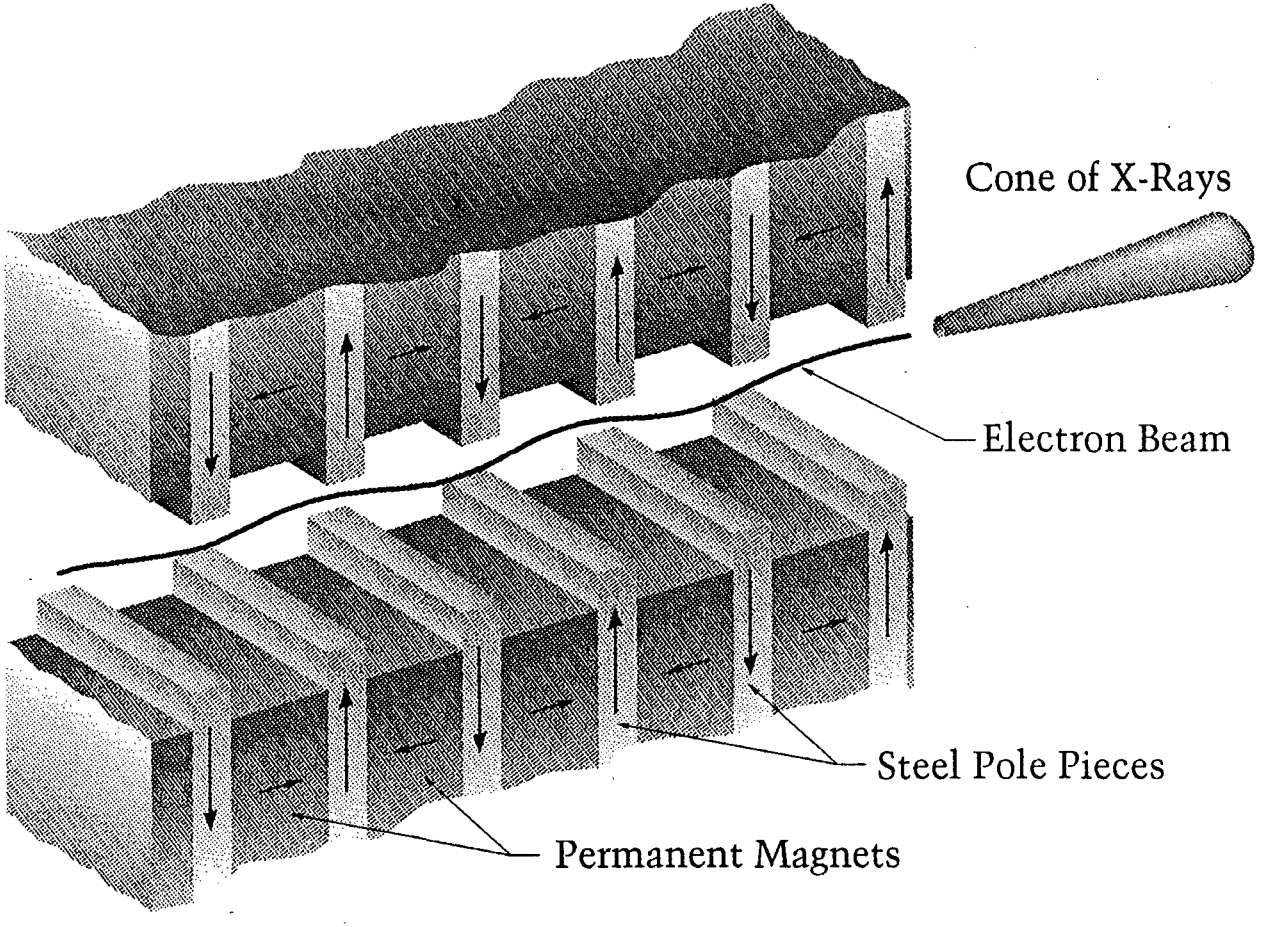

Fig. 2. Schematic drawing of an undulator based on high-field permanent magnets that produce alternating magnetic dipoles along the device. Undulators are used to produce high-brightness beams of ultraviolet and x-ray photons. Since the energy of these photons depends in part on the magnetic field within the undulator, one can vary the energy of the undulator radiation by mechanically adjusting the gap between the top and bottom portions of the undulator. [Figure 2 is from page 23 of the journal article by Arthur L. Robinson cited in our bibliography.]

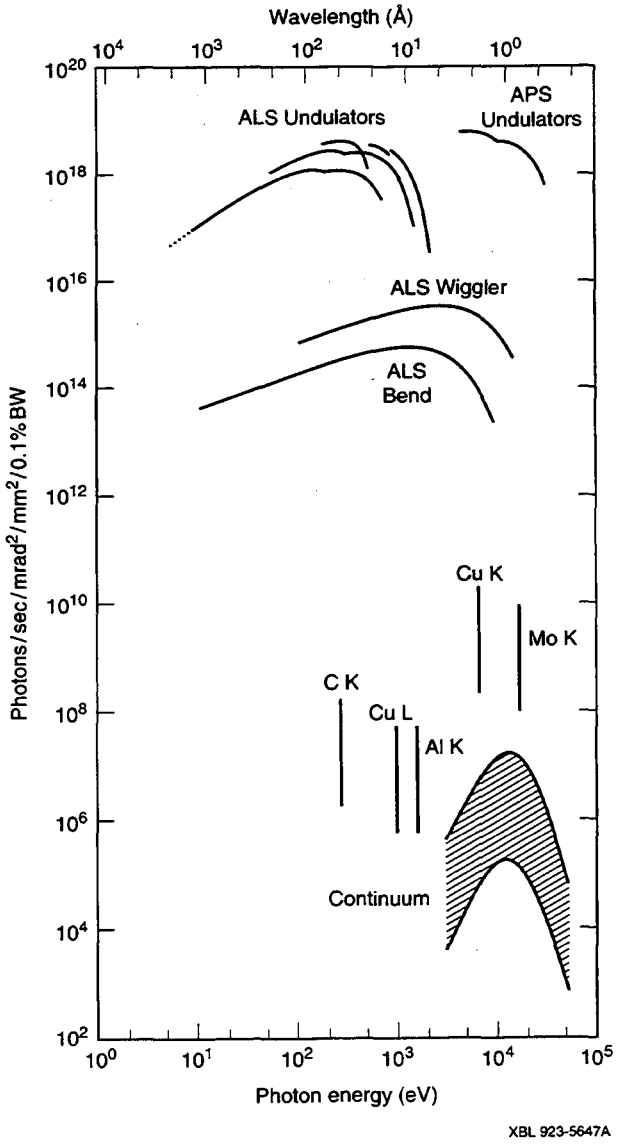

Fig. 3. Spectral brightness curves comparing the Advanced Light Source and the Advanced Photon Source with conventional x-ray sources found in the laboratory. Spectral brightness is the brightness within a narrow band of wavelengths (bandwidth) around the nominal wavelength. For the undulators, the curves represent the envelope traced out by the fundamental and harmonics as the magnetic field, and thus the photon energy, changes. [Diagram courtesy of the Lawrence Berkeley Laboratory]

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