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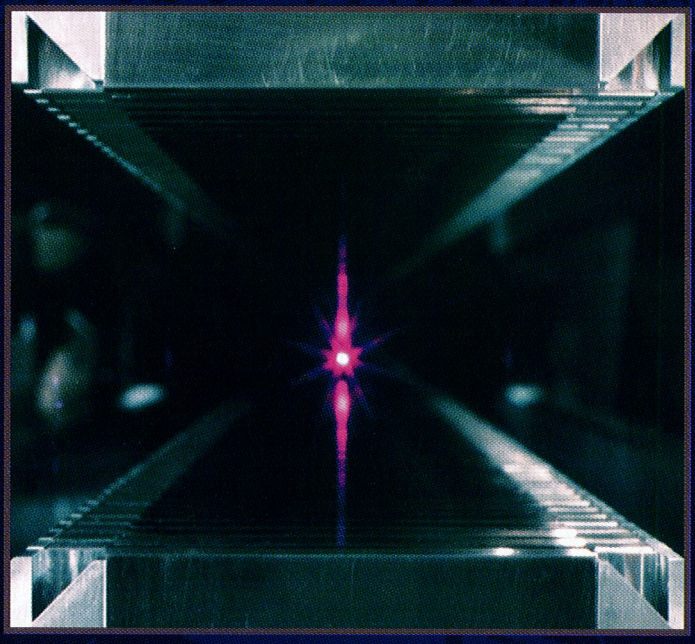
BRIGHT BEAMS: The Advanced Light Source



Lawrence
Berkeley
Laboratory

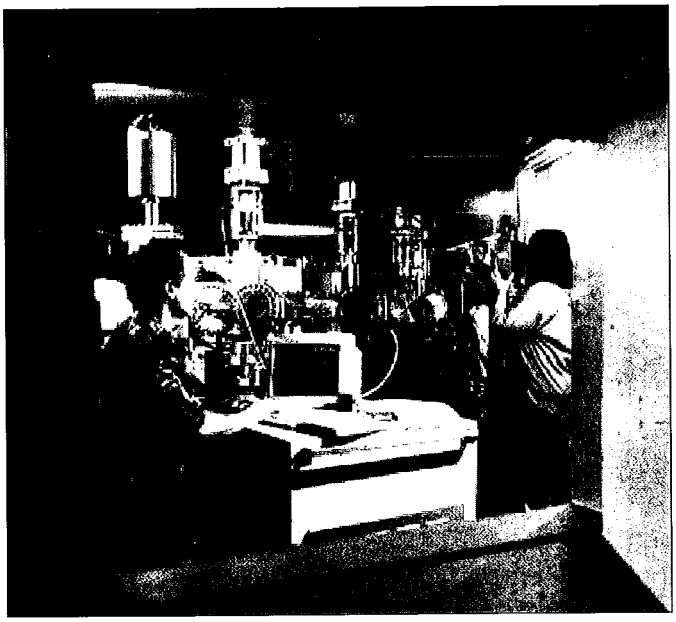
LIGHTING THE WAY

THE BRIGHT BEAMS OF THE ADVANCED LIGHT SOURCE WILL MARK LBL'S MOVE INTO THE SCIENCE OF THE 21ST CENTURY

ALS

It began under the Laboratory directorship of David A. Shirley. It was completed under the directorship of Charles V. Shank. Jay Marx oversaw its construction. Brian Kincaid is overseeing its operation. It has been the most talked about and eagerly awaited project at LBL since it was first proposed nearly 10 years ago. The wait is finally over. Now it is here.

"It" is the Advanced Light Source (ALS)—a $100 million synchrotron radiation source capable of boosting the energies of electrons to 1.5 billion electron volts (GeV) and extracting from them laserlike beams of x-ray and ultraviolet light that will outshine any in the world. Its premier beams, in the soft (low-energy) x-ray and extreme ultraviolet region of the electromagnetic spectrum, will be from 20 to 100 times brighter than beams from other synchrotron radiation sources and a hundred million times brighter than the light from the most powerful x-ray tubes.



▶ **The synchrotron radiation ports (covered circular openings) of an arc sector of the ALS storage ring are visible through an opening in the radiation shielding. Taking test data are Richard DeMarco (left), Dennis Merrill, and Donna Jones.**

The x-ray and ultraviolet light from the ALS, collectively known as XUV radiation, will serve scientists from across the nation and around the globe in a broad number of fields. Materials scientists are getting a spectroscopic probe that can focus on surface areas only a few hundred atoms in diameter, identifying which elements are present and how their electrons are arranged or how they could be rearranged for new applications. Chemists get a camera that can freeze-frame lightning-fast chemical reactions, such as combustion, at less than a billionth of a second for step-by-step observations of what is taking place. Biologists and other life scientists will have an x-ray microscope that can peer deep inside living cells in their natural state and perhaps provide the first truly three-dimensional images of the structures within.

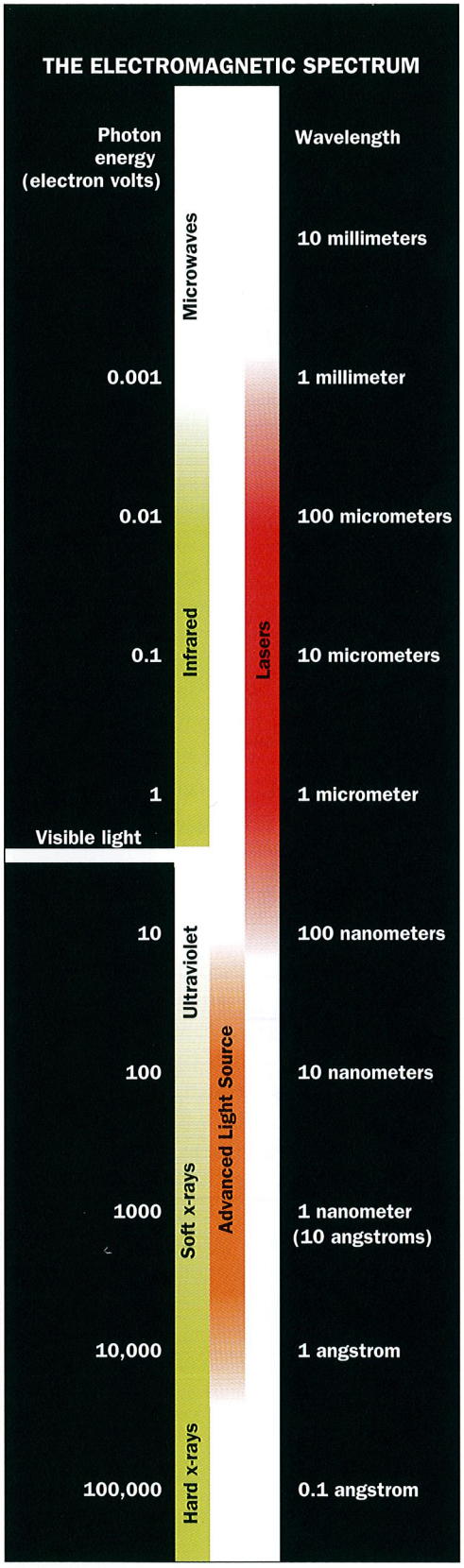
▲ **ALS Director Brian Kincaid (right) points out features of an ALS undulator to Howard Bryant of the University of New Mexico at the fifth annual ALS Users' Association meeting.**

The ALS could also play a major role in the development of one of the hottest new technologies on the horizon—nanotechnology. From supercomputers that fit in the palm of the hand to self-assembling, molecular-sized machines that clean up our environment and conserve energy, major opportunities lie with nanostructures—devices less than a millionth of a meter in size.

A key to achieving this future is x-ray lithography (see sidebar, page 12). Through x-ray lithography, patterns with features as tiny as a hundred nanometers (about 1/1000th the thickness of a human hair) can be transferred onto materials to make such exotic creations as a gigabit memory chip—one that contains 64 times more information than today's most advanced microchips. ALS x-rays are ideal for studying and testing the optical systems and coatings used in x-ray lithography and other nanostructure research.

The versatility of the ALS stems from the quality of its XUV radiation beams. These beams have properties similar to laser light—they are exceptionally bright and highly monochromatic, and they are coherent, meaning that individual light waves are all the same frequency and phase, and travel in the same direction. ALS radiation is also tunable: its wavelengths can be varied, and pulsed: it flashes on and off like a strobe light. The pulse rates of ALS beams can be as high as 500 million pulses per second, with each lasting only 30 to 40 picoseconds (trillionths of a second). This allows the ALS to function as a highly effective stop-action camera.

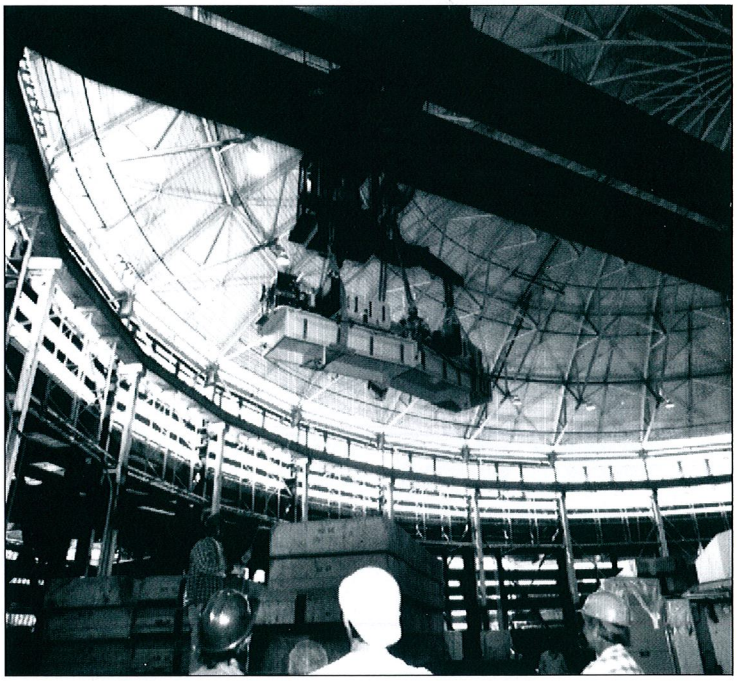
In addition to their unique combination of spectral features and high brightness, the soft x-ray beams of the ALS will match the primary atomic resonances of many important elements, including carbon, oxygen and silicon. Other types of ALS beams extend this match to almost every element on the periodic table. What this means, among other things, is that ALS photons are readily absorbed by the atoms of these elements. When atoms absorb photons, they eject electrons, with the energy and number of electrons ejected



dependent upon the frequency and brightness of the light. Analysis of absorption spectra or of the associated photoelectron spectra yields information about the electronic configurations of the atoms. These configurations are, in general, responsible for the physical properties of substances, including appearance, texture, freezing and melting temperatures, electrical conductivity, and so on.

The ALS is located on the site where LBL founder Ernest O. Lawrence built the 184-inch cyclotron during World War II. (The 184-inch took its name from the diameter of the magnet's pole faces.) Although much of Lawrence's "184" had to be demolished to make room for the ALS, the dome that crowned the old accelerator and became a Berkeley landmark was preserved. The building underneath the dome, however, with a floor space of approximately two acres, is nearly four times larger than the previous structure.

Housed inside this building are a pair of electron accelerators and a state-of-the-art electron storage ring. The accelerator complex, which serves to inject the electrons into the storage ring, consists of a linear accelerator, or "linac," that can lift

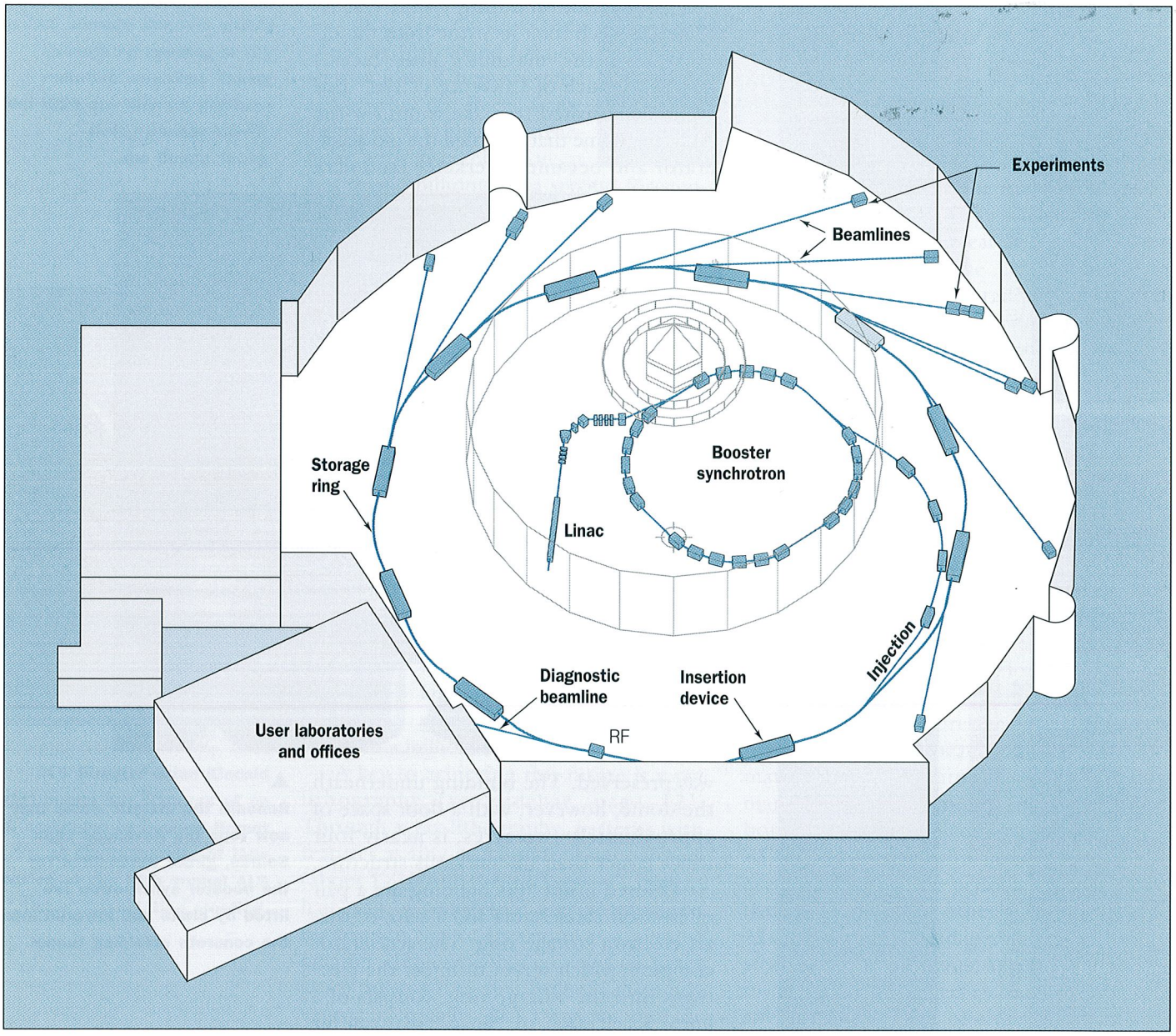


▲ **Beneath the historic dome that now tops the Advanced Light Source, girder assemblies for the booster synchrotron are lifted by crane and lowered into the concrete shielding tunnel.**

The Advanced Light Source's main components are a linear accelerator (linac), a booster synchrotron, and an electron storage ring with bending and focusing magnets and insertion devices. Beamlines lead to experimental areas. ▼

the energies of electrons to 50 million electron volts (MeV) and a small booster synchrotron for raising those 50 MeVs to 1.5 billion electron volts (GeV). The storage ring is designed to circulate the 1.5 GeV electrons for many hours in a tightly constrained, ribbon-shaped beam no thicker than a human hair.

This storage ring consists of 12 arc-shaped sections joined by 12 straight sections, each 6 meters (about 20 feet) long. One of these straight sections receives the electrons injected from the booster synchrotron into the storage ring, and another contains the radio-frequency power system that replenishes the energy lost by the electrons as they orbit. The remaining straight sections have been built to accommodate special magnetic "insertion" devices called undulators and wigglers. With its design optimized for high-performance undulators, the premier sources of synchrotron light, the ALS is a so-called "third-generation" synchrotron light



source—one of the first members of a forthcoming international family of such machines.

Synchrotron light is the electromagnetic radiation emitted by electrons when their speed or direction of motion is changed. This radiation can be in the XUV region of the spectrum when the electrons are forced to travel along a curved path at speeds approaching the speed of light. Synchrotron accelerators, which use dipole "bending" magnets to curve the paths of accelerating electrons into circular orbits, produce copious amounts of synchrotron light in a sweeping beam that is similar to that of a beacon.

Synchrotron light was once an unwanted by-product in accelerator storage rings. High-energy physicists trying to maintain the boosted energy levels of electrons were not happy that some of this precious energy was being lost through emitted photons. Eventually, however, scientists in other disciplines learned to put the light to good use, which led to the demand for much greater, more intense quantities of photons. The result was a recognition of the usefulness of undulators and wigglers and the subsequent advancement of insertion-device technology.

An insertion device is an array of dipole magnets with alternating north and south poles. The reversing polarity of an insertion device forces a beam of electrons speeding through it to oscillate sideways, causing the electrons to emit light in a direction tangential to the path of the beam. The wavelength of light produced depends on the wavelength and amplitude of the oscillations and energy of the electrons.

Undulators generate laserlike beams as a result of the constructive interference in the emission of light from each oscillation of the electron beam. This interference compresses the radiation into a few narrow spectral peaks. The wavelength of the light produced by an undulator can be tuned by mechanically expanding or reducing the gap between the undulator's array of magnetic poles. Wigglers, on the other hand, emit light in a nearly continuous spectrum, just as bending magnets. However, unlike the sweeping beacon of light from bending magnets, the light from a wiggler is directed, like that of a flashlight.

The ALS storage ring has room for 10 insertion devices and will probably contain eight undulators and two wigglers. The undulators can be up to 4.6 meters in length (nearly twice as long as most existing synchrotron insertion devices) and can feature a variety of periods, which is the distance in the array from one north pole to the next. Smallest is an undulator with a period of 3.9 centimeters—dubbed "U3.9"—which provides soft x-rays at energies from less than 200 electron volts (eV) up to 2500 eV, a range which covers the so-called "water-window" for penetrating and imaging biological objects. The undulator with the longest period will be U10 (10 centimeter period), which will cover the energies around 6 eV and will be used in studies of chemical dynamics. In between these are U5, which will provide the photons in the 52 to 1900 eV range for studies of materials, surfaces and interfaces, and U8, with photons ranging from 8 to 1100 eV, which will shed light on atoms, ions, and molecules.

One wiggler in the ALS will be 2.9 meters long, with a period of 16 centimeters (W16). Light from the W16 wiggler will extend beyond 10,000 eV, which is the realm of hard x-rays, and will be useful in x-ray crystallography studies and spectroscopy research. Such light will also serve as a highly sensitive x-ray microprobe with a spatial resolution approaching one micron.

The second wiggler—not yet designed—will probably be what is known as an "elliptical wiggler." This type produces

Workers install a section of the vacuum chamber in the storage ring. The concrete shielding walls and roof now enclose the entire ring.
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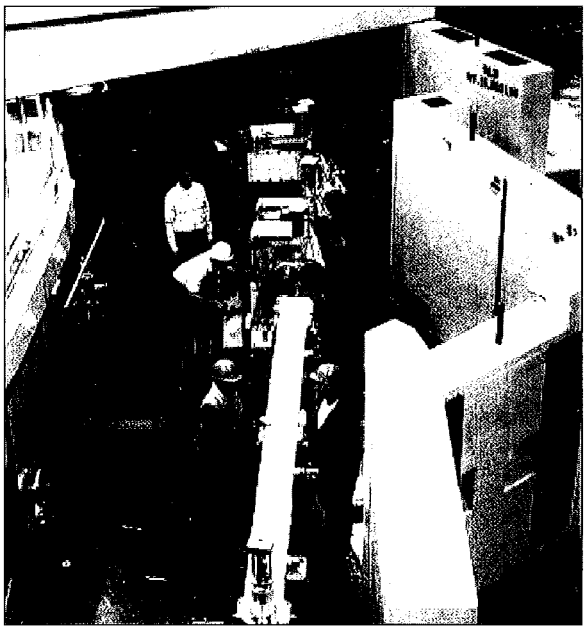


Teaming Up With Industry

LBL's Advanced Light Source has been designated by the U.S. Department of Energy (DOE) as a national user facility. This means that its powerful beams of laserlike x-rays are available for use by qualified scientists and engineers from throughout the country—not only researchers from other national laboratories and universities but private industry as well.

Glen Dahlbacka is in charge of industrial program development for LBL's Technology Transfer Department. A physicist with extensive experience in x-ray science, he came to LBL from Maxwell-Brobeck Laboratories, builders of synchrotron light sources and equipment, where he was vice-president of business development.

Dahlbacka believes that private industry could eventually account for as much as 30 percent of ALS beam use. He sees four principal areas of opportunity for companies—microscopic machines, structural biology, analytical services (metrology, spectroscopy, etc.) and x-ray microscopy.

▲ **Glen Dahlbacka**

Microscopic machines, also known as micro-electromechanical systems or MEMS, are considered to be the hottest things to hit the high-technology market since integrated circuits. Though they were once thought to be the stuff of science fiction, the global market for MEMS has already reached $500 million and is expected to soar to $8 billion by the turn of the century.

The key to the fabrication of future MEMS is lithography techniques (similar to what is used in the production of integrated circuits), using the types of x-rays that the ALS will generate in abundance.

Explains Dahlbacka, "The MEMS being made with visible light lithography are essentially two-dimensional devices. The penetration obtained with light beams from the ALS will make possible the fabrication of three-dimensional MEMS."

In the area of structural biology, one of the most promising applications of the ALS is x-ray protein crystallography. Among other things, this would help pharmaceutical companies design more effective drugs.

"In the past, the designing of new pharmaceutical drugs has been a discovery process because the structure of a given protein could only be estimated," says Dahlbacka. "Knowing the precise structure of a protein would enable the intelligent design of drugs to fit or modify an enzyme for special chemical jobs. There is also strong industrial interest in x-ray microscopy, another very useful tool for studying chemically sensitive biological and surface structures."

The x-ray microscope, a microprobe beamline, and a spectroscopy facility will form the core instruments for the analytic services offered at the ALS.

Private industry research groups seeking to work on the ALS can do so in a number of ways, Dahlbacka says. The quickest and easiest is for the group to become what is called an ALS "participating research team." Such teams contribute to the costs of constructing and operating an ALS experimental facility for either an insertion device beamline or a bending magnet beamline. In return, participating research teams are guaranteed a percentage of beamtime, depending on the extent of their contribution to the project.

The commitment of a participating research team is six years for an insertion device beamline and four years for a bending magnet beamline. Companies wanting time on the ALS but unable to make such long-term commitments might hire LBL to do the research under a work-for-others contract. They might also negotiate a Cooperative Research and Development Agreement (CRADA) with LBL through DOE.

"There is a growing awareness of the capability of the national laboratories to quickly contribute value back into the U.S. economy," Dahlbacka says. "Through user facilities such as the ALS, and new contractual tools and funds provided by the legislation, LBL has accepted this added mission and is ready to act." —LY

circularly polarized XUV radiation, which is particularly useful for probing both magnetic materials and "chiral" molecules— those that have a left-handed or right-handed character to their structure.

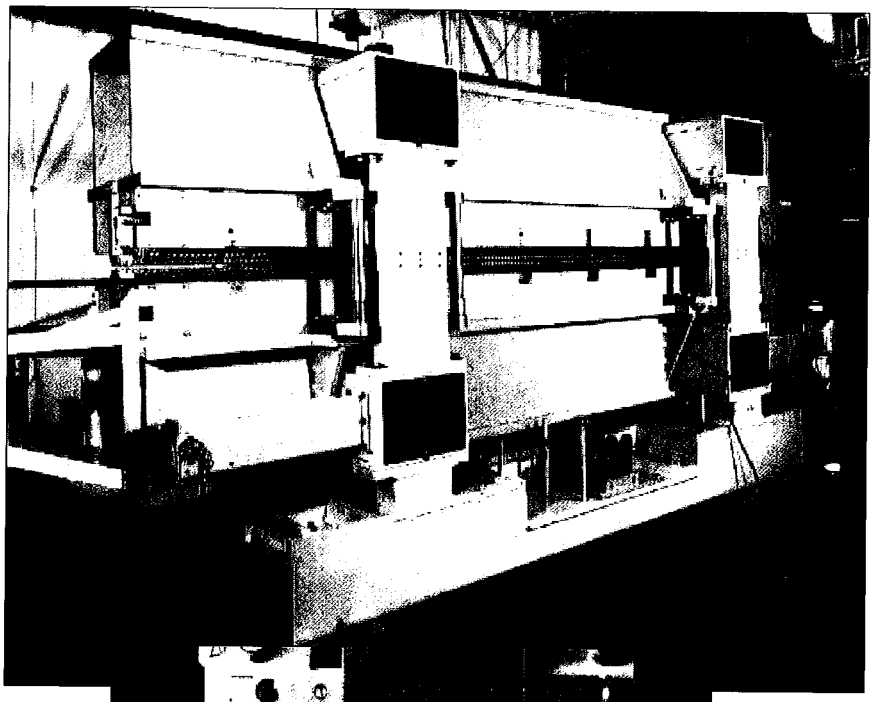
The development at LBL of permanent-magnet wigglers and undulators was a major factor in making it possible for the ALS and other third-generation synchrotron radiation facilities to produce their bright beams. Unlike electromagnets, permanent-magnets require neither expensive electrical power nor space-consuming coils to generate their magnetic fields. Consequently, their poles can be spaced close enough together to obtain x-ray wavelengths of light.

In addition to the light from its insertion devices, the ALS can also generate light, including hard x-rays, through the bending magnets in the arc sections of its storage ring. Although the synchrotron light from the ALS bending magnets is not as bright as that from the ALS insertion devices, it compares very favorably with the light from other synchrotron bending magnet sources because of the high quality of the ALS' electron beam.

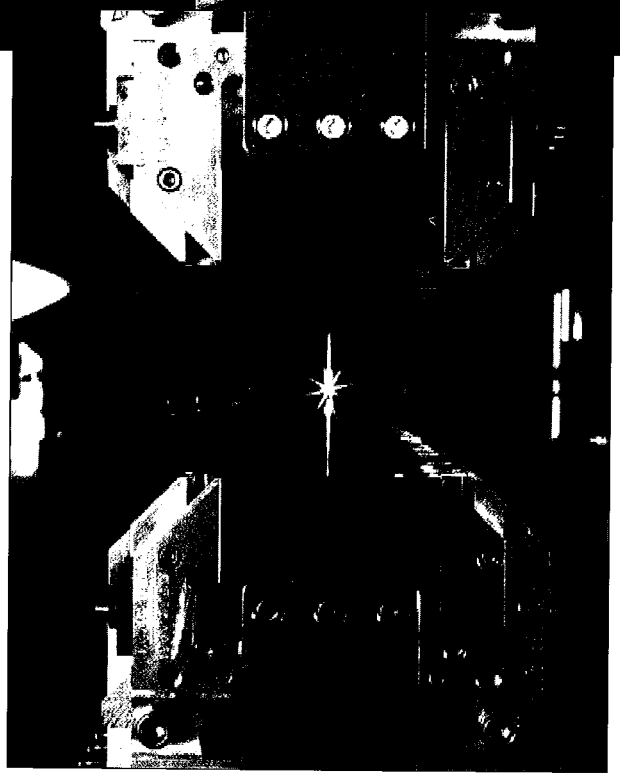
Crucial to getting optimal performances from the ALS insertion devices is the quality of the storage ring's electron beam. Rather than a continuous stream of particles, the electron beam in the ALS' storage ring is formed from discrete bunches of electrons. These discrete bunches are what makes the ALS light pulsed, giving it a strobed effect and enabling it to initiate and track the progress of time-dependent processes such as chemical reactions.

ALS electrons are created by a high-intensity electron gun that can generate single or multiple bunches of 120,000 eV electrons in pulses of 2.5 nanoseconds (billionths of a second). As electrons emerge from the gun, they pass through two "subharmonic bunchers" (frequencies of 125 and 500 megahertz, respectively) that compress the beam first into pulses of 800 picoseconds, then into 200-picosecond pulses. The beam is then fed into the accelerating structures of the 50 MeV linac.

The 1.5 GeV booster synchrotron into which the injection system feeds its 50



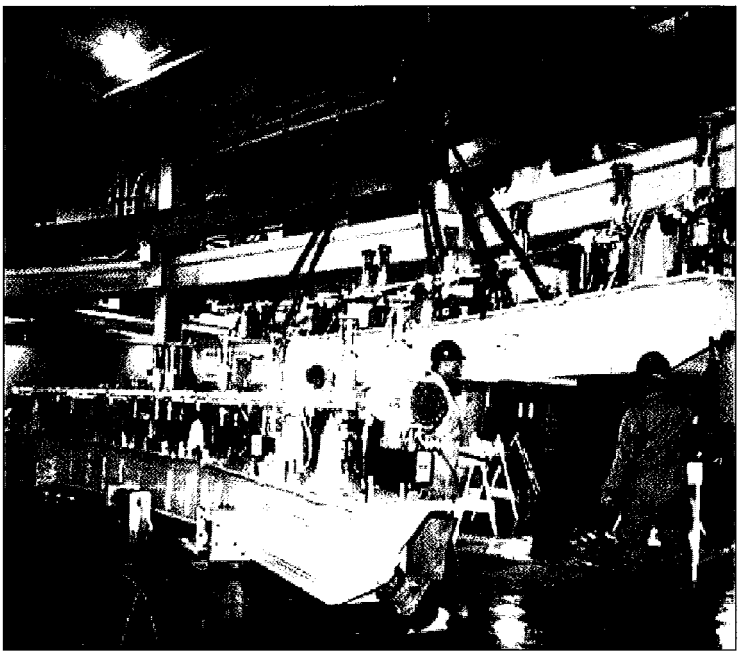
▲ **The two magnet arrays for the first undulator are installed in their support structure, which is capable of resisting a force of up to 42 tons.**



◀ **Simulating an electron beam, a strobe light shines through the two arrays of magnets in an ALS undulator. The gap between the upper and lower rows of magnets can be changed to alter the wavelength.**

MeV electrons is composed of 24 dipole magnets, 32 quadrupole magnets, and 20 sextupoles, distributed over 12 girders. Every second, the booster sends pulses of 1.5 GeV electrons into the storage ring, filling the ring in about five minutes. It is in the storage ring where electron beam quality is maintained at an unprecedented level of excellence.

Another precisely positioned armada of magnets and a complex vacuum system are the keys. Each of the ring's 12 arc-shaped sections contain three dipole bending magnets, six quadrupole magnets that focus the electron beam, and four sextupole magnets that correct for the spread of electron energies. This arrangement, called a "triple bend achromat," stabilizes the beam and keeps emittance—a product of beam size and divergence—exceptionally low, while the electrons orbit around the ring for six hours, covering a distance equivalent to that from the Earth to the planet Neptune (about 2.7 billion miles).



▲ **An arc section of the storage ring is lowered into place. Mounted atop the girders is the vacuum chamber, through which electrons will travel; the vertical structures actuate the photon stops that absorb escaping photons.**

The ALS storage ring's vacuum chamber is a worthy complement to its unique lattice of magnets. Nothing must impede the flight of electrons in a storage ring, so they travel through a chamber-encased channel that has been evacuated. Maintaining the vacuum of this channel is complicated by the fact that the circling electrons are continually emitting photons that can desorb gas from the chamber walls. The ALS vacuum chamber is designed to permit most of these photons to escape the channel through a slot into an antechamber, where they are absorbed by photon stops. Any gas that is produced is removed through a series of pumps.

After light is extracted from the ALS storage ring, it is sent through beam lines, branched off and directed into experimental areas by means of special mirrors and optical devices. Light from the undulators can appear over a range of XUV wavelengths, depending on the magnetic field, and light from the wigglers and bending magnets covers a broad, continuous spectrum. To customize this light for their own specific purposes, scientists at the different experimental areas can select specific wavelengths, using a monochromator.

Monochromators employ a combination of slits and gratings to disperse photons and collect the wavelengths of interest. Because conventional gratings cannot handle the intense beam of energetic photons produced in the ALS insertion devices, LBL scientists and engineers designed and fabricated a prototype for a new type of high-resolution monochromator. This new monochromator features a unique water-cooled spherical grating that rotates about an axis under computer control to scan the wavelengths of incoming photons. The grating is made from a nickel-coated copper alloy that can withstand the power of the ALS' light, and its spherical surface is super-smooth and precisely shaped to preserve the light's high brightness.

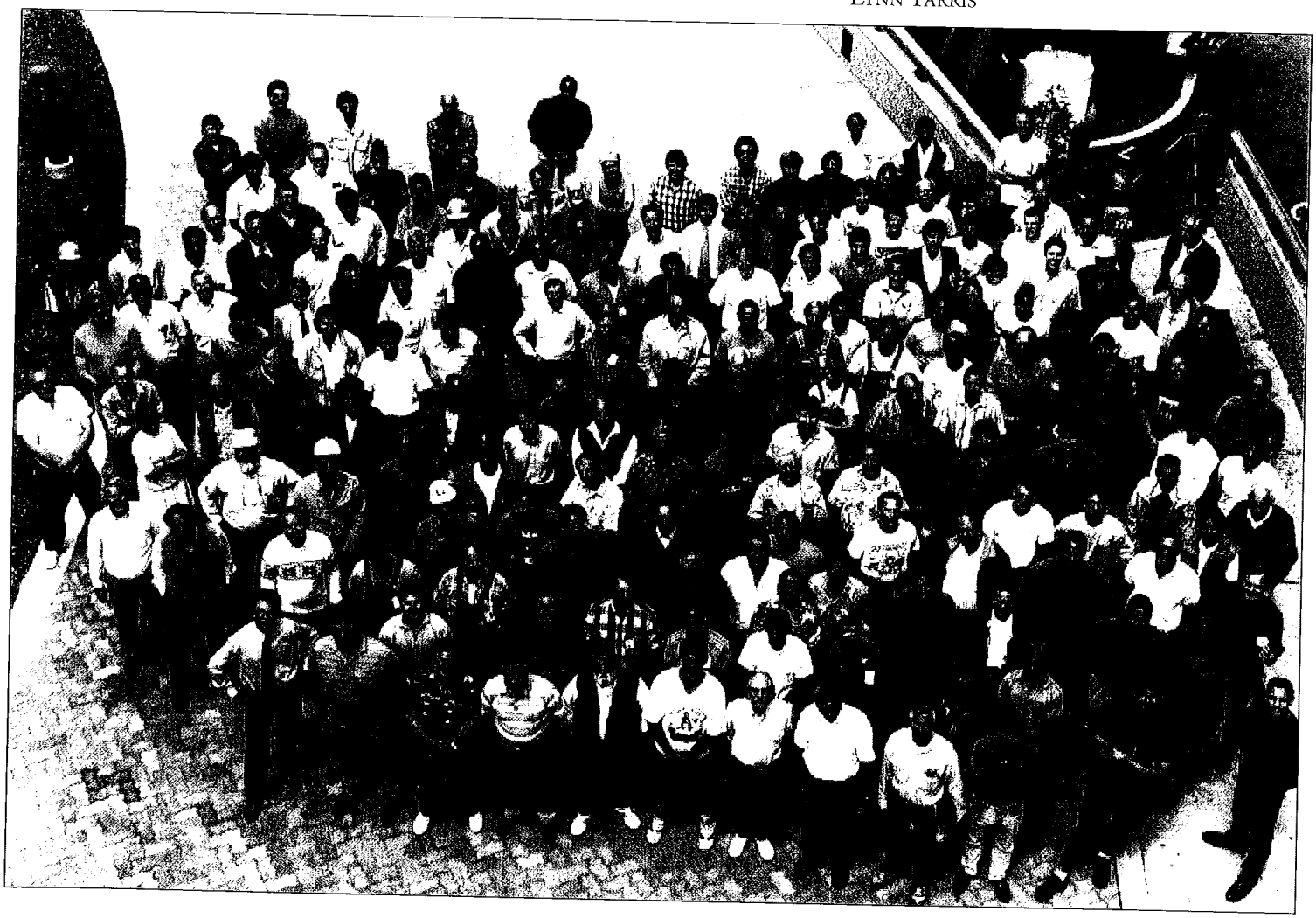
During its first year, the ALS will have up to six beamlines, including five for scientific research and one that is used for beam diagnostic purposes. Three of the scientific beamlines gener-

ate their light from undulators. One of the two lines built at LBL is equipped with a photoelectron spectrometer and two microscopes that can provide a resolution of 500 angstroms or better for spectromicroscopy research. The other will be used to investigate atomic and molecular photoprocesses. The third undulator beamline, built at IBM's Almaden Research Center, will be used for photoelectron spectroscopy and for soft x-ray emission and absorption spectroscopy.

The other two scientific beamlines at the ALS obtain their light from bending magnets. One of these beamlines was formerly operated at the Stanford Synchrotron Radiation Laboratory. Relocated and modified to take advantage of the ALS' brighter light, this beamline will be used to study problems in materials and chemical sciences. The other bending magnet beamline, built by researchers at LBL's Center for X-ray Optics, will serve as a "white-light" microprobe to detect and measure the presence of trace amounts of elements—amounts as small as a millionth of a billionth of a gram.

Five more scientific beamlines will be added to the ALS complement within the next two years.

The ALS has been designated by the U.S. Department of Energy as a national user facility and will be available for research purposes to qualified scientists and engineers. Hundreds of researchers from throughout the world are expected to visit the facility each year. LB

—LYNN YARRIS

A staff of more than 100 people worked to bring the ALS from conception to completion.