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Advanced Light Source: Ultraviolet and Soft X-Ray Beams for Research

Permalink
https://escholarship.org/uc/item/1797d7vw

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Publication Date
1993
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ADVANCED LIGHT SOURCE
Ultraviolet and Soft X-Ray Beams for Research

LAWRENCE BERKELEY LABORATORY
THE ADVANCED LIGHT SOURCE is situated in the hills of Berkeley, California, overlooking the San Francisco Bay. Its new building, with floor space of about two acres (8100 square meters), incorporates the dome that once covered the 184-Inch Cyclotron built by Lawrence Berkeley Laboratory's founder E.O. Lawrence.
THE ADVANCED LIGHT SOURCE (ALS) is a national facility for scientific research and development located at the Lawrence Berkeley Laboratory of the University of California. Its purpose is to generate beams of very bright light in the far ultraviolet and soft x-ray regions of the spectrum. Within these regions, the ALS produces the world’s brightest light available as an experimental tool. This $99.5 million facility, funded by the U.S. Department of Energy, is available to qualified researchers from industry, universities, and government laboratories.

At the ALS, researchers can conduct experiments not yet possible anywhere else in the world, and the information they gain can lead to new products of tremendous economic importance.

X-ray beams from the ALS can help the electronics industry develop tools for fabricating integrated circuits with features smaller than 0.25 micron. (A micron is one-millionth of a meter.)

Pharmaceutical scientists can use ALS light to determine the three-dimensional molecular structure of crystalline proteins. This technique is of great benefit in designing new drugs.

Materials scientists can use the light to study the composition of polymer blends—important work in the development of new plastic materials that are friendly to the environment, yet strong enough to be used in automobiles.

### How Small Is Small?

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 meter</td>
<td>1,000,000 microns</td>
</tr>
<tr>
<td>Diameter of</td>
<td>~80 microns</td>
</tr>
<tr>
<td>human hair</td>
<td></td>
</tr>
<tr>
<td>1 micron</td>
<td>10,000 angstroms</td>
</tr>
<tr>
<td>1 angstrom</td>
<td>~one-millionth the diameter of a human hair</td>
</tr>
</tbody>
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Scientists in the computer industry can study the data-storage capacity of new magnetic materials. For example, they can use ALS light to take pictures of the bits stored on a computer disk. This work is expected to lead to dramatic increases in storage density.

CONSTRUCTION OF THE ALS BUILDING began in 1988. Leaders of the project were (left to right) Jay Marx, Project Director; Ron Yourd, Project Manager for Construction; Brian M. Kincaid, Project Deputy Director (Experimental Systems); and Alan Jackson, Project Deputy Director (Accelerator Systems).
LIGHT IS ONE OF THE MOST important tools of science. It is the key to viewing the universe—from distant galaxies to cells, molecules, and even atoms. Light has a dual nature, behaving both as a stream of massless particles (photons) and as electromagnetic waves moving through space.

Visible light, which enables us to see the everyday objects around us, is easily generated and easy to detect. The sun, electric lamps, and fire produce it. We can see visible light with our eyes and detect it with photographic film. But it constitutes only a tiny fraction of the full spectrum of light in the universe—known as the electromagnetic spectrum.

The remainder of the spectrum consists of light with wavelengths larger or smaller than those of visible light. On the larger side are radio waves, microwaves, and infrared radiation. Smaller-wavelength light includes ultraviolet, x rays, and gamma rays. These regions of the spectrum are invisible to the eye and must be detected by special means. Each region has a range of wavelengths and photon energies that determine the degree to which the light will penetrate and interact with matter.

The ALS is designed to generate light principally in the far ultraviolet and soft x-ray regions of the spectrum. This light is useful because:

• It can penetrate materials opaque to visible light. Everyone is familiar with dental or medical x rays, which penetrate our skin and muscle tissue to reveal images of bone.

• It has the right wavelengths—from about \(10^{-7}\) to \(10^{-10}\) meter—for exploring the atomic structure of solids, molecules, and important biological structures. The sizes of atoms, molecules, and proteins as well as the lengths of chemical bonds and the minimum distances between atomic planes in crystals are in this range.

• It has photon energies from about 10 to 10,000 electron volts. (An electron volt is equivalent to the energy an electron attains if accelerated by 1 volt.) This energy range includes the binding energies of many electrons in atoms, molecules, solids, and biological systems. Thus, when absorbed by an atom, a photon can cause an electron to separate from the atom or can cause the emission of other photons. By detecting and analyzing such electron or photon emission, scientists learn about the properties of the sample.

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THE SPECTRUM OF LIGHT covers a wide range of wavelengths and photon energies. Light used to visualize an object must have a wavelength comparable to the object's dimensions. The ALS generates extremely bright light in the far ultraviolet and soft x-ray regions, which span the wavelengths suited to studying molecules and atoms. Therefore, this light is an excellent probe of the structure of matter.
HAND IMAGE was made in 1896 by Wilhelm C. Roentgen, who discovered x rays and put them to practical use.

IMAGE OF A CHROMOSOME from a larva of the midge (a tiny fly) was obtained through x-ray microscopy. Although the banding structure can be seen through a visible-light microscope, an x-ray microscope was required to capture the filamentary structure between the bands.

CHEMICAL COMPOSITION of a microfabricated sample (a) was determined through a technique called spectromicroscopy. After absorbing x rays, the sample emitted electrons with energies characteristic of its components. Analysis of these energies identified and mapped sections of aluminum (b), pure silicon (c), and silicon dioxide (d).

ATOMS, chemical bonds, and the distances between atomic planes in crystals all measure a few angstroms—comparable to the wavelengths of light from the ALS.
WHENEVER A CHARGED PARTICLE such as an electron is accelerated or decelerated, it produces photons. Because a change in the direction of motion is a form of acceleration, a beam of electrons forced to follow a curved path also emits photons. If the electrons become relativistic (approach very closely the speed of light), the number of photons and their energy increase dramatically, and the photons are emitted in a narrow, forward-directed cone.

Light generated by bending the path of relativistic electrons is called synchrotron radiation. The ALS generates light according to this principle.

At the ALS, an electron gun shoots electrons into a linear accelerator (or linac), which accelerates them to an energy of 50 million electron volts. The electrons are then injected into a booster synchrotron for further acceleration—to 1.5 billion electron volts. At this energy, the electrons are moving at 99.999996% of the speed of light. From the booster, the electrons enter a storage ring with a diameter two-thirds the length of a football field, where they circulate for hours at constant energy.

In the storage ring, the electron beam travels through a vacuum chamber in a sequence of 12 arc-shaped sections alternating with 12 straight sections. The arc sections are imbedded in a lattice of bending and focusing magnets that force the beam into a curved trajectory and constrain it to a tight ellipse no thicker than a human hair. As the electrons curve through an arc

A BEAM OF ELECTRONS travelling in a curved path at nearly the speed of light emits a photon beam. The beam fans out at an angle $\theta$, the natural emission angle.

THE ALS LINAC accelerates the electrons from an electron gun inside the cabin (far left) toward the transfer line leading to the booster.
section, beams of synchrotron radiation emerge from three ports, each corresponding with a bending magnet in the arc. The straight sections, which have no focusing or bending magnets, are used for other purposes. One is the site of electron injection from the booster. Another houses two radio-frequency (rf) cavities in which

**THE ALS STORAGE RING** has 12 arc-shaped and 12 straight sections. The arc sections are imbedded in a magnetic lattice that consists of 12 magnet sequences, one for each arc. Each sequence contains three bending magnets (B), six quadrupole magnets (Q), and four sextupole magnets (S). Relativistic electrons, accelerated by the linac and booster synchrotron, travel through the storage ring generating synchrotron radiation.
AN ELECTRON BEAM circling the ALS storage ring is divided into bunches by oscillating radio-frequency fields that replenish the electron beam’s energy. Consequently, the synchrotron radiation emitted by the electron beam is pulsed rather than continuous.

Electromagnetic fields oscillate at a frequency of 500 MHz (500 million times per second). These fields replenish the electron beam’s energy lost to synchrotron radiation. Because of their oscillating nature, they also divide the electron beam into bunches. Thus, an observer looking into the vacuum chamber would see that the circulating electrons do not form a continuous stream of particles. Instead, the electrons come in discrete bunches separated by empty spaces. As a result, the synchrotron radiation emitted by the bunched electron beam is not emitted continuously but in a pulsed fashion.

The 10 remaining straight sections are designed to accommodate devices called undulators and wigglers, which generate synchrotron radiation with enhanced characteristics. Collectively termed “insertion devices,” undulators and wigglers consist of two arrays of permanent magnets that create a magnetic field of alternating polarity perpendicular to the electron beam. One array is installed above and the other below the vacuum chamber. The alternating polarity causes the beam to wiggle or undulate horizontally from side to side as it passes between the rows of magnets. As the electrons curve back and forth, they emit synchrotron radiation. As a result, a wiggler produces a continuous spectrum of radiation, similar to that produced by a bending magnet that has the same magnetic field strength—but radiation produced by a wiggler is more intense. The angle at which an undulator’s magnets deflect electrons is close to the natural emission angle of the radiation. Consequently, the waves of light emitted at each pole in the array reinforce or cancel one another to enhance the emission of certain wavelengths at certain emission angles. For this reason, undulator radiation at the enhanced wavelengths is extremely bright—brighter than either bending magnet or wiggler radiation. And because it emerges in a narrow cone and is partially coherent, it is similar to the light from a laser.
The storage ring has one port for the light from each undulator and wiggler—a maximum of 10 insertion-device ports—in addition to 36 bending-magnet ports. Light transmitted through these ports travels through beamlines to experimental stations where it is put to use. These beamlines are fitted with optics such as mirrors and monochromators to focus the light and improve its energy resolution. (A monochromator is a device used to select a narrow range of the available wavelengths in the beam of synchrotron radiation.)

The majority of the ALS beamlines are built by participating research teams (PRTs), which customize the optics for their experiments. PRTs make their equipment available to other researchers approved to conduct experiments on the beamline.

**Layout of the ALS** shows the linac, booster, storage ring, beamlines, and experimental areas. A typical beamline contains a monochromator, mirrors, and other optical components to guide the synchrotron radiation from the storage ring to an experiment.
A major benefit of brightness is high spatial resolution (or focusability). High spatial resolution is achieved because many photons can be focused on an extremely small spot and can therefore provide information about extremely small objects. The smaller the focal spot, the smaller the object that can be distinguished from its surroundings. With help from special optical devices, the ALS is expected to achieve spot sizes less than 1000 angstroms in diameter.

A second benefit of brightness is high spectral resolution. By narrowing the slits at the entrance and exit of a monochromator, one can select a very narrow range of wavelengths from a beam of synchrotron radiation—and in this way achieve very high spectral (or energy) resolution. But narrowing the slits also decreases the number of photons that pass through and therefore increases the time it would take to make measurements using these photons. With extremely bright light, like that from the ALS, a larger number of photons can be focused through the slits; thus, at a fixed measurement time, resolution increases with brightness, or, at a fixed resolution, the measurement time decreases. As a result, experiments that once were impractical because of insufficient resolution or long measurement times have now become feasible.

SYNCHROTRON RADIATION
has certain characteristics that, individually or combined, allow researchers to perform experiments not otherwise possible:

- Very high brightness.
- Tunability.
- Pulsed nature.
- Linear or circular polarization.
- High degree of coherence.

Of these, the most prized characteristic is high brightness, a measure of the light’s concentration. The rays of light are very intense and occupy a small cross-sectional area. The ALS delivers the world’s brightest synchrotron radiation in the far ultraviolet and soft x-ray regions of the spectrum.

MATERIAL SURFACES and the interfaces between materials are highly complex. Many physical, chemical, and biological processes occur there in tiny, scattered areas. With light from the ALS, scientists can find and study processes occurring in areas less than 1000 angstroms in diameter (one-thousandth the diameter of a human hair).
Apart from the issue of spectral resolution, the **tunability** of synchrotron radiation is important in itself. From the range of available wavelengths in a beam, one can select a specific wavelength (or photon energy) and tune out the others. For example, a wavelength might be selected because an atom in a sample exhibits a sharp increase in the absorption of light at this wavelength. X-ray absorption spectroscopy, a family of analytical techniques based on the absorption of light by atoms, can reveal the identity, electronic structure, and chemical bonding state of the absorbing atom and provide information about the identity, number, and arrangement of the neighboring atoms.

Synchrotron radiation is **naturally pulsed** because the electrons producing the radiation travel in bunches. Standard pulses delivered by the ALS are 35 picoseconds (trillionths of a second) wide at half maximum and occur at intervals of 2 nanoseconds (billionths of a second). This time structure can be varied by injecting only one or a few electron bunches into the storage ring. In this few-bunch mode, the ALS delivers pulses at much longer intervals.

The pulsed nature of the light, the high flux (rate of photon delivery), and the ability to vary the interval between pulses make it possible to perform timed-resolved studies—for example, on the kinetics of a chemical reaction or the lifetime of excited states of atoms or molecules. The high flux guarantees that there are enough photons per pulse to induce a measurable signal from the irradiated species. The extremely narrow width and rapid frequency of the standard pulses make it possible to investigate ultrafast processes, whereas the ability to lengthen the interval between pulses allows the study of processes with relatively long lifetimes.

Synchrotron radiation produced by the ALS also has the useful

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**X-RAY MICROPROBE** built at the Lawrence Berkeley Laboratory uses a pair of mirrors coated with multilayers to focus a beam of x rays to a spot several microns in diameter. The beam apertures further reduce the spot size to about 2 microns. The three-dimensional graph illustrates the capability of the microprobe to detect trace amounts of impurities. In this example, the tall peaks represent iron impurities detected in a silicon carbide ceramic substrate. They came from stainless steel tweezers used to handle the ceramic.

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**CHEMICAL REACTIONS** can be investigated with pulsed light from two sources in “pump-probe” experiments. A pump pulse of synchrotron radiation initiates a chemical reaction that is interrogated by a probe pulse from a laser.
THE UNIQUE PROPERTY of circularly polarized light is the spiral path of its electric-field component. This component maps out a clockwise or counterclockwise circular path to form a right-handed or left-handed spiral.

CHIRAL MOLECULES are mirror images that cannot be superimposed—like left and right hands. The pair of chiral molecules shown here are examples of amino acids, the building blocks of proteins.

such as DNA or amino acids [the building blocks of proteins] lend themselves to experiments with circularly polarized synchrotron radiation.

Because of their inherent directional spin, magnetic materials can also exhibit dichroism. Scientists have exploited this phenomenon by using circularly polarized synchrotron radiation in conjunction with an imaging microscope to obtain pictures of bits, as small as 10 microns × 1 micron, on a computer's magnetic storage disk. It was possible to obtain these images because each bit corresponds to a magnetic region with its own direction of magnetization. This

IMAGE OF MAGNETIC BITS on a storage disk was obtained by subtracting two images recorded with right circularly polarized synchrotron radiation tuned to the cobalt L₁ and L₂ x-ray absorption edges (wavelengths at which cobalt exhibits increased absorption). The magnetization direction of the bits lies along the rows but points alternately to the right and to the left in the picture. The dimensions of the bits in the three rows are (from top row, in microns) 10 × 10, 10 × 2, and 10 × 1.
type of research can lead to a greater understanding of the magnetic characteristics of materials and possibly to the development of new materials with greatly increased magnetic storage capacity.

Undulators at the ALS can produce synchrotron radiation that is highly coherent—the light waves are nearly all of the same wavelength, and they all travel in phase or with a constant phase difference. (When light waves travel in phase, their peaks coincide.) Although not so coherent as the visible light from most lasers, undulator radiation has much more coherence than ever before available in the far ultraviolet and soft x-ray regions of the spectrum. One of the most exciting uses for coherent synchrotron radiation is holography. While laser light can be used to make holograms of objects that we can see, coherent x rays can image objects that are far smaller.

Coherent synchrotron radiation might also be used to test the quality of optical lenses and mirrors used in x-ray applications—for example, x-ray astronomy, x-ray lithography for manufacturing microchips, and x-ray imaging of microstructures in biology and materials science. The smaller the object imaged, the greater the demand for high-quality optics polished to eliminate virtually all defects. The ALS is the world’s first source of coherent x rays for the testing of x-ray optics.

Beams of ultraviolet and soft x-ray light from the ALS are extremely bright, tunable, pulsed, polarized, and partially coherent. Because of these characteristics, they lend themselves to a host of scientific techniques. Their use is limited only by the bounds of creativity. By shedding new light on the intricacies of matter, the ALS will contribute immensely to the nation’s technology and long-term economic health.

X-RAY HOLOGRAM (top) contains the information needed to create a reconstructed image of zymogen granules (bottom), which appear as dark spherical objects. These are storage vesicles for digestive enzymes found in a pancreatic cell. Such images can reveal information about digestion mechanisms. The shading of the zymogen granules indicates their density. The darker a granule, the more dense it is, indicating a larger enzyme content.
For More Information

If you would like more information about the ALS, or if you have an interest in conducting research at this facility, please contact:

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Credits

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Hand image, page 3, column 1, from Wilhelm Conrad Roentgen, the Early History of Roentgen Rays by O. Glasser (John Bale Sons and Danielson Limited, London, 1934).

Chromosome image, page 3, column 2, produced by G. Schmahl and M. Robert-Nicoud, University of Göttingen, at the BESSY synchrotron radiation facility, Berlin, Germany.

Microfabricated sample images, page 3, column 3, based on work done by scientists from the State University of New York at Stony Brook, IBM, and the Lawrence Berkeley Laboratory. Data were taken at the National Synchrotron Light Source, Upton, NY.

X-ray microprobe example, page 9, based on work done by Albert C. Thompson and Karen L. Chapman of the Lawrence Berkeley Laboratory. Data were taken at the National Synchrotron Light Source, Upton, NY.

Image of magnetic bits, page 10, produced by scientists from the IBM Almaden Research Center and the University of Wisconsin, Milwaukee, at Stanford Synchrotron Radiation Laboratory, Stanford, CA.


January 1993

This brochure was published prior to the start of operations at the ALS. For this reason, it contains examples of research conducted at other synchrotron radiation facilities.

Technical writing by Gloria Lawler.  
Photographs of ALS facilities by Steve Adams of the Lawrence Berkeley Laboratory.

UNDULATOR used at the ALS has two 4.55-meter arrays of permanent magnets of alternating polarity. The arrays are supported by a superstructure capable of resisting the force of their attraction—up to 42 tons. As an electron beam passes through a vacuum chamber between the arrays, the magnets cause the beam to curve back and forth and thus produce synchrotron radiation. Undulators produce light brighter than that from other types of synchrotron radiation sources and with the added characteristics of partial coherence and linear polarization. In this photograph, a strobe light emulates the electron beam.