Title
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Author
Schlachter, F.

Publication Date
1996

LBNL-38807
UC-410
Preprint

Ernest Orlando Lawrence Berkeley National Laboratory

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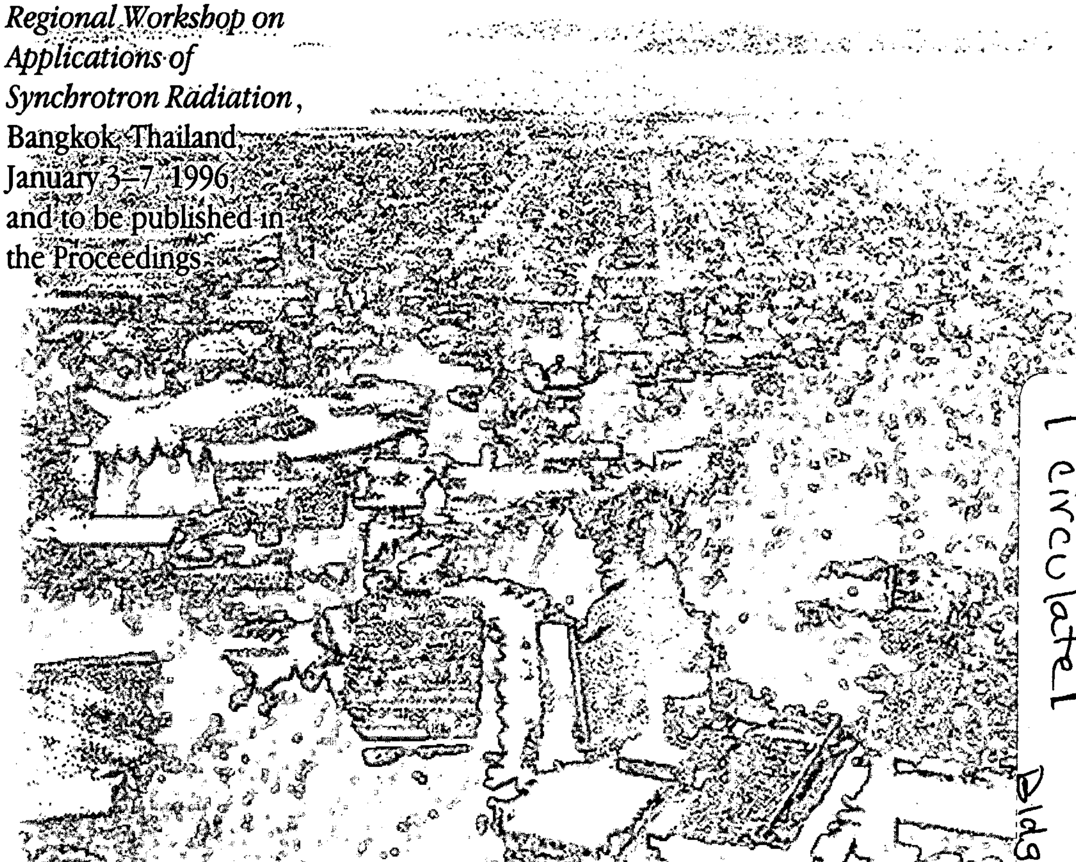
F. Schlachter and A. Robinson
Accelerator and Fusion Research Division

January 1996
Presented at the
Regional Workshop on Applications of Synchrotron Radiation,
Bangkok, Thailand,
January 3–7, 1996,
and to be published in
the Proceedings



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LBNL-38807
LSGN-216
UC-410

SYNCHROTRON LIGHT SOURCES: A POWERFUL TOOL FOR SCIENCE AND TECHNOLOGY*

Fred Schlachter and Art Robinson

Advanced Light Source
Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720 USA

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Paper presented at the Regional Workshop on Applications of Synchrotron Radiation
Chulalongkorn University, Bangkok, Thailand, January 3-7, 1996

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U. S. Department of Energy, under Contract No. DE-AC03-76SF00098.

Synchrotron Light Sources: A Powerful Tool for Science and Technology

Fred Schlachter and Art Robinson
Advanced Light Source
Lawrence Berkeley National Laboratory
Berkeley, CA 94720 USA

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.

Visible light, which enables us to see the everyday objects in the world 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; however, it constitutes only a tiny fraction of the full electromagnetic spectrum. The remainder of the spectrum consists of light with wavelengths longer or shorter than those of visible light. On the longer side are radio waves, microwaves, and infrared radiation. Shorter-wavelength light includes ultraviolet light and x rays. Radiation in these regions of the spectrum is invisible to the eye and must be detected by other means (Figure 1).

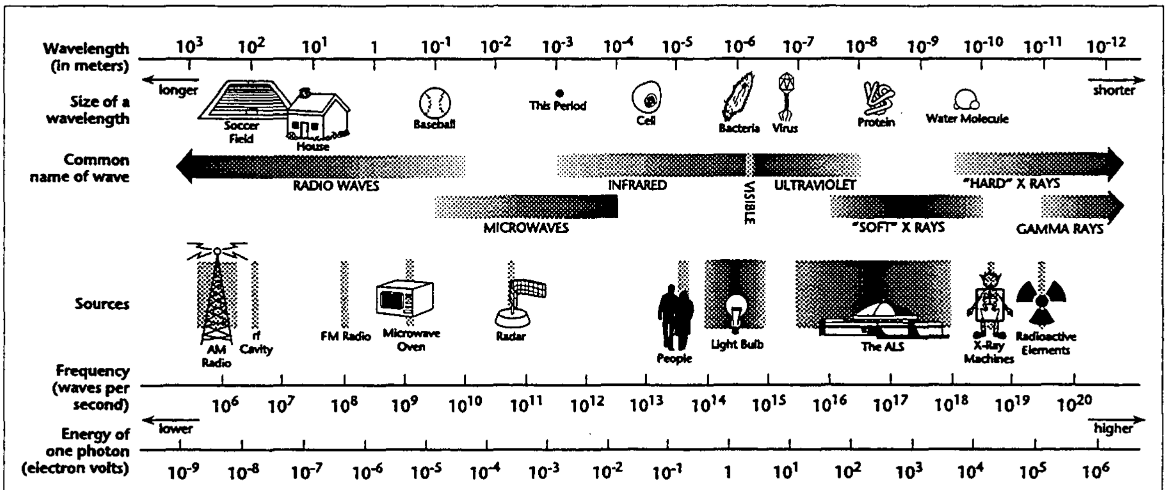

Figure 1. The electromagnetic spectrum.

Radiation in the ultraviolet and soft x-ray regions of the spectrum is of particular interest to scientists for several reasons:

- It can penetrate material opaque to visible light.
- It has the right wavelengths—in the angstrom region—for exploring the atomic structure of solids, molecules, and biological entities.
- It has photon energies corresponding to the binding energies of inner-shell electrons of light elements, a feature that permits the exploration of the electronic structure of matter.

X rays can thus be used as a powerful probe of matter. Two essential tools for the study of matter using x rays are spectroscopy, which determines what elements or chemical bonds are present in a sample, and microscopy, which can determine the spatial arrangement of matter in a sample of interest. The properties of high-brightness x rays produced at third-generation synchrotron light sources such as the Advanced Light Source (ALS) can be exploited for both spectroscopy and microscopy studies.

The Production of Synchrotron Radiation

The production of x rays by a synchrotron source begins with a relativistic beam of electrons (or positrons) circulating in a specialized accelerator storage ring. Whenever one of the electrons is accelerated, it emits radiation in the form of photons. In the vacuum of the storage ring, electrons traveling near the speed of light are bent and focused by magnetic fields. Any energy lost due to emitted radiation is replaced by radio-frequency waves.

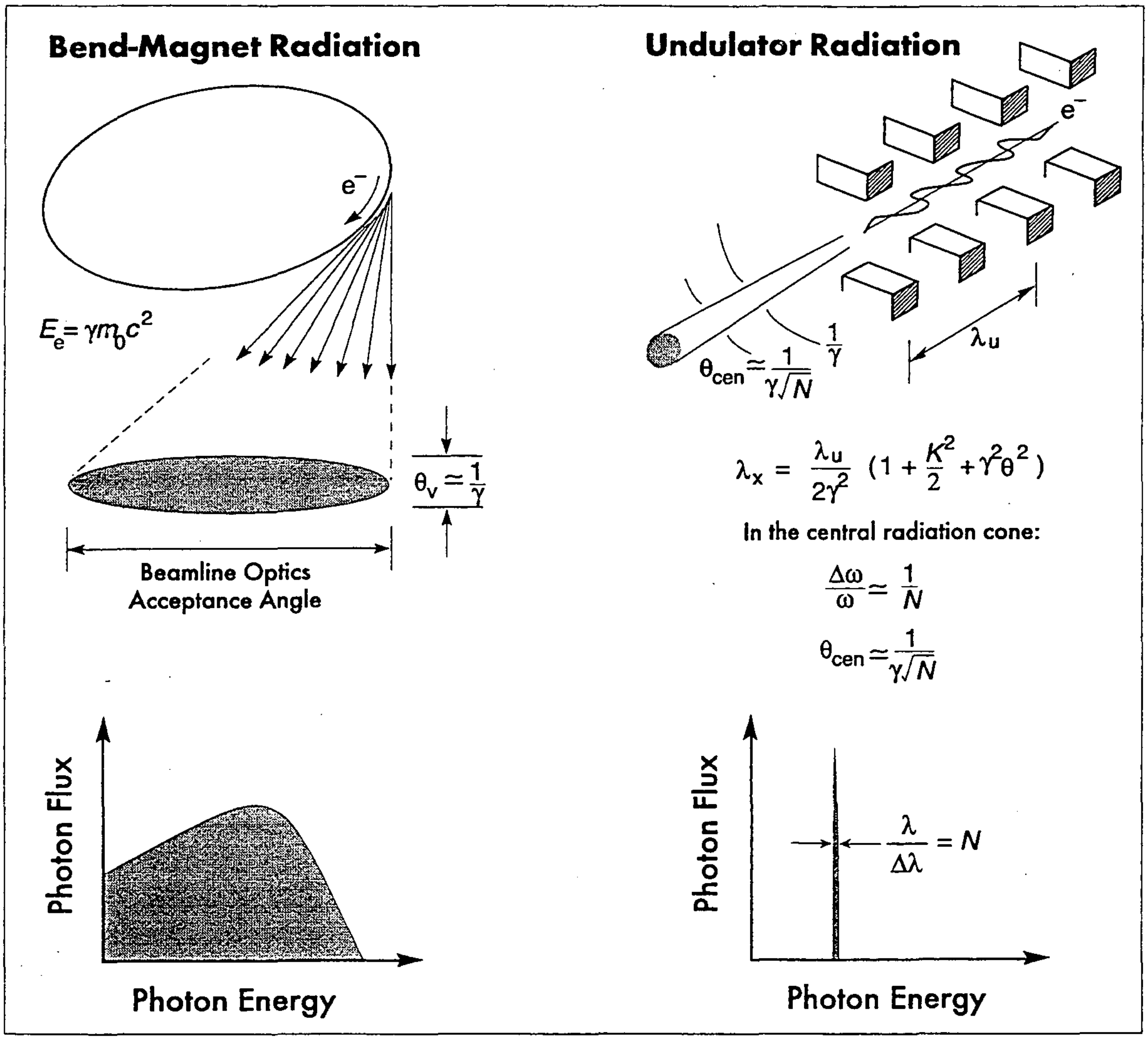

Figure 2. The light produced at synchrotron sources comes from bend magnets, where relativistic electrons are accelerated in a dipole magnetic field, and from undulators, where a spatially alternating magnetic field produced by an array of dipole magnets leads to a coherent superposition of radiation from each bend, producing an extremely bright and nearly monochromatic photon beam.

Several features of synchrotron radiation make it a powerful tool for research:

Continuous spectrum. Synchrotron radiation comprises a broad, continuous spectrum of wavelengths with the highest photon flux (photons per second) at ultraviolet or x-ray wavelengths depending on the energy of the accelerator—the higher the energy, the shorter the accessible wavelength.

High flux. The flux from a synchrotron light source is generally far higher than that from conventional sources, increasing signal and reducing measurement time for most experiments. In many cases, the enhanced signal makes possible experiments that are prohibitively lengthy using conventional laboratory sources.

High brightness. The synchrotron radiation beam is highly collimated due to the strong forward (i.e., tangential to the curved path) emission of synchrotron light into a narrow cone a few hundredths of a degree wide. The high collimation combined with the small size of the source of the light (the electron beam) makes for high brightness, allowing experiments with high spectral resolution, high spatial resolution, or both (spectromicroscopy).

Pulsed beam. Since the electron beam in an accelerator consists of a succession of "bunches" with spaces between, the synchrotron light is pulsed rather than continuous. Pulsed light makes it possible to follow the progression of a process, such as a chemical reaction, by using one pulse to initiate a process and subsequent pulses to observe events as they take place in real time.

High coherence. The high coherence of synchrotron radiation from a high-brightness source at longer wavelengths allows interferometry and other studies in holography, optics, and x-ray imaging.

Linear or circular polarization. Synchrotron radiation can be produced with a high degree of linear or circular polarization. Polarized light can be used to study the orientation of molecules in matter or on a surface, or to study the orientation of magnetization in magnetic materials.

Third-Generation Light Sources

Two features characterize third-generation synchrotron light sources. One is the inclusion of long straight sections for undulators in the storage ring, because brightness increases with undulator length. The second is a refinement of storage-ring design to reduce the emittance, because brightness is inversely proportional to emittance squared. Long undulators in a low-emittance storage ring produce synchrotron light that is truly laser-like. Furthermore, wigglers and bend magnets also benefit from the low emittance, and third-generation facilities effectively utilize all three type of sources. Third-generation light sources are in planning, construction or operational stages in many parts of the world for several reasons:

- They are the world's brightest sources of x rays for scientific research.
- They promise some of the most intimate looks yet at the structure, composition, and chemical bonding of almost any solid, liquid, or gaseous material, from semiconductors to biological molecules.
- They can contribute to technology development for industries whose world-wide markets total more than $750 billion.

Synchrotron-radiation facilities provide an outstanding tool for research and development in science and technology on regional and national scales, and they create an excellent training environment for students. Moreover, the design and construction of a facility promote the development of a sophisticated engineering and fabrication infrastructure in the regional economy.

Brightness

The most prized characteristic of light produced at third-generation synchrotron sources is high brightness, which arises from high total flux (photons/second), small source size, and narrow radiation solid angle. Lasers, whose high-intensity, needle-like beams have transformed optical science in the infrared and visible regions of the spectrum, illustrate both the properties and the virtues of high brightness.

Although the requirements for brightness differ from experiment to experiment, generally a brighter beam is far more useful because the light remains concentrated in a small beam over long distances. With high brightness, researchers can do experiments faster, record higher-resolution spectra, examine smaller samples or parts of samples less than 1 micrometer in size, and follow structural changes on a nanosecond time scale.

Third-generation synchrotron light sources are roughly 100 times brighter than the best existing second-generation synchrotron sources and 100 million times brighter than conventional x-ray sources found in the laboratory. X-ray brightness has continued to increase at a dramatic rate ever since the 1960's, gaining ten orders of magnitude since 1960. Contrast this with the very slow increase in the world land speed record for automobiles which has only increased from 206 km/hr in the early 1900's to the present record of 1020 km/hr (Figure 3).

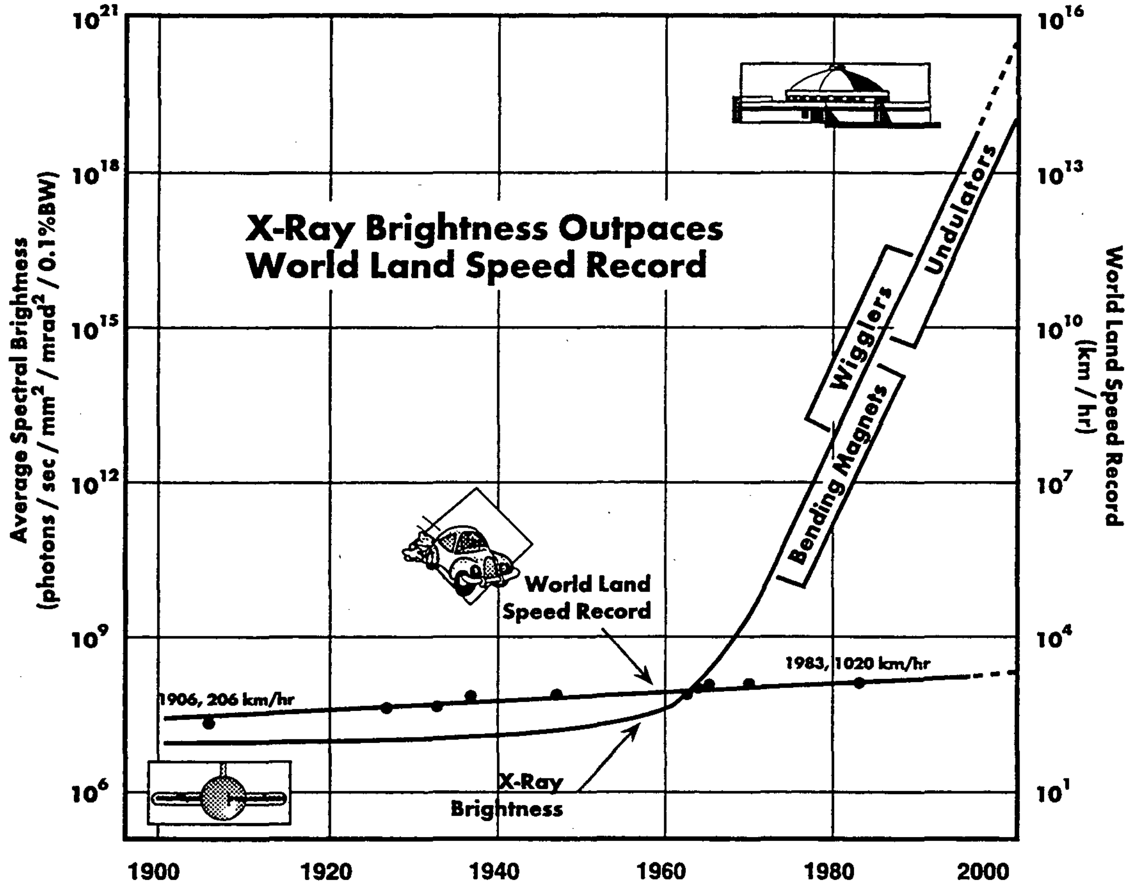

Figure 3. If the land speed record had kept pace with improvements in x-ray brightness, cars would now travel nearly one million times the speed of light (10^{15} km/hr).

High Spectral Resolution

High brightness leads to high spectral and high spatial resolution. High brightness undulator radiation can be focused to fill the entrance slit of a monochromator, thus providing high spectral resolution with high flux. This allows study of narrow spectral features, providing detailed information, for example, about atomic or molecular energy levels (Figure 4).

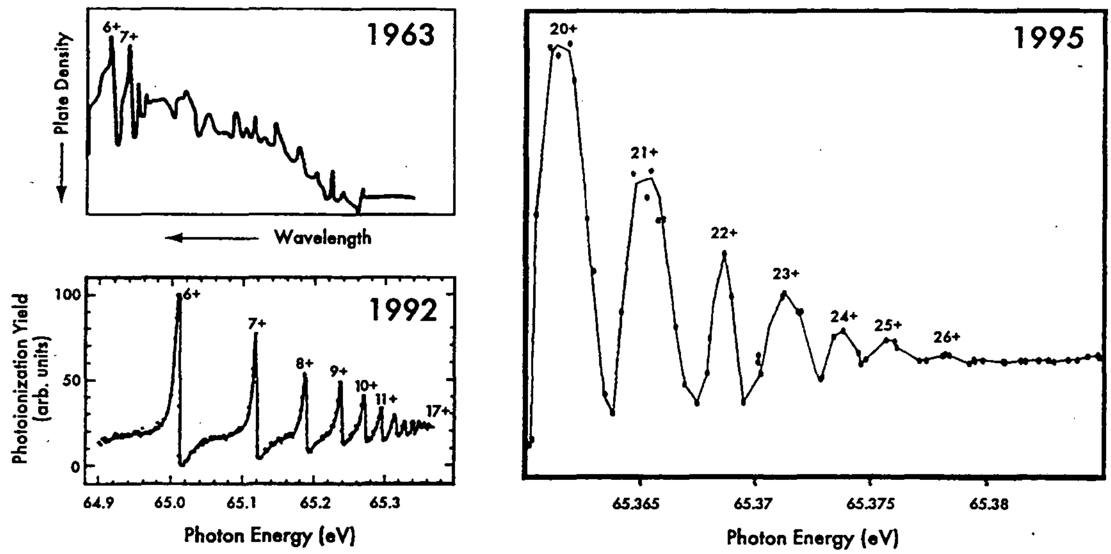

Figure 4. *Increasing spectral resolution allows researchers to observe ever-smaller spectral features, as these spectra from doubly excited states of helium show. (1963 spectrum from Madden and Codling; 1992 spectrum from Reich et al.; 1995 spectrum from collaborative effort of Freie Universität Berlin and the Advanced Light Source.)*

Elemental contrast can be easily obtained by photoemission or fluorescence spectroscopy. Chemical-bond identification can be made using photoemission spectroscopy or near-edge absorption spectroscopy. This is particularly useful in distinguishing between elements in different but related molecules (e.g., Si and SiO or SiO_2) or between various polymers.

High Spatial Resolution

Whether semiconductor chips, magnetic storage disks, high-strength metal alloys, ceramics, plastics, or sub-cellular structures in biological cells, most materials share the common characteristic of being heterogeneous, which is to say that the structure, composition, and chemical bonding are not the same throughout the material. The sizes of samples and of the features to be examined therein are constantly decreasing. A familiar example is that of microcircuits, in which the size of characteristic features in circuit patterns is dropping toward 0.1 micrometer (100 nanometers). Whereas previous synchrotron measurements involved averaging signal over all or most of a sample, undulator light can now be focused to provide spatial resolution, either by scanning the sample with a small spot or by imaging a larger field (Figure 5). The ability to examine small areas in detail advances the applicability of synchrotron radiation to real-world materials. Zone plates and multilayer reflective optics provide the "lenses" for shorter-wavelength light, which cannot be focused with the lenses used for visible light. Imaging zone-plate microscopy has provided rich images of cells (Figure 6).

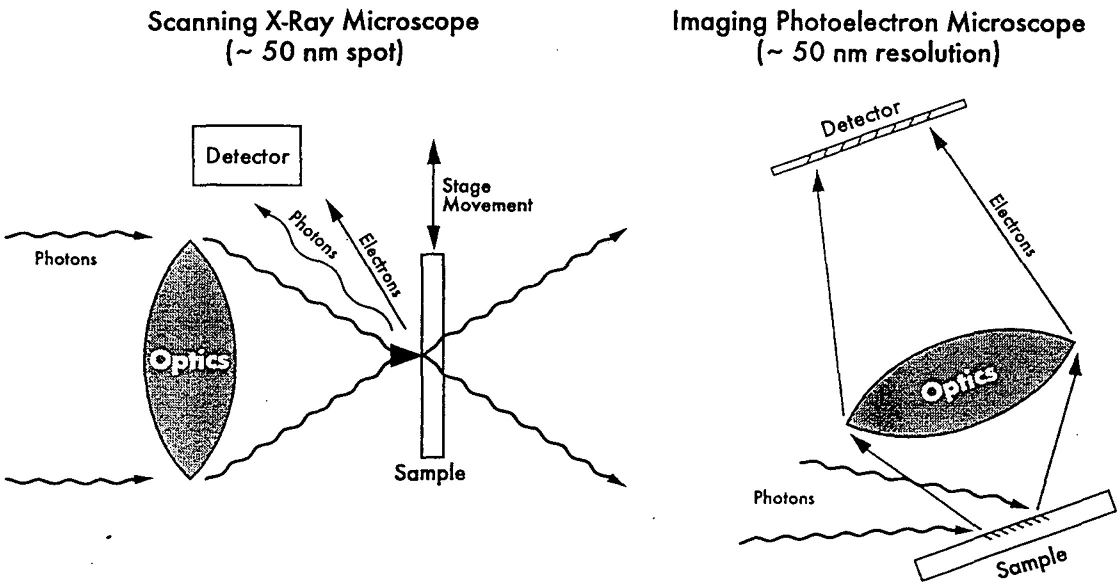

Figure 5. *Both scanning and imaging x-ray microscopes can take advantage of high-brightness synchrotron light to produce images at high resolution.*

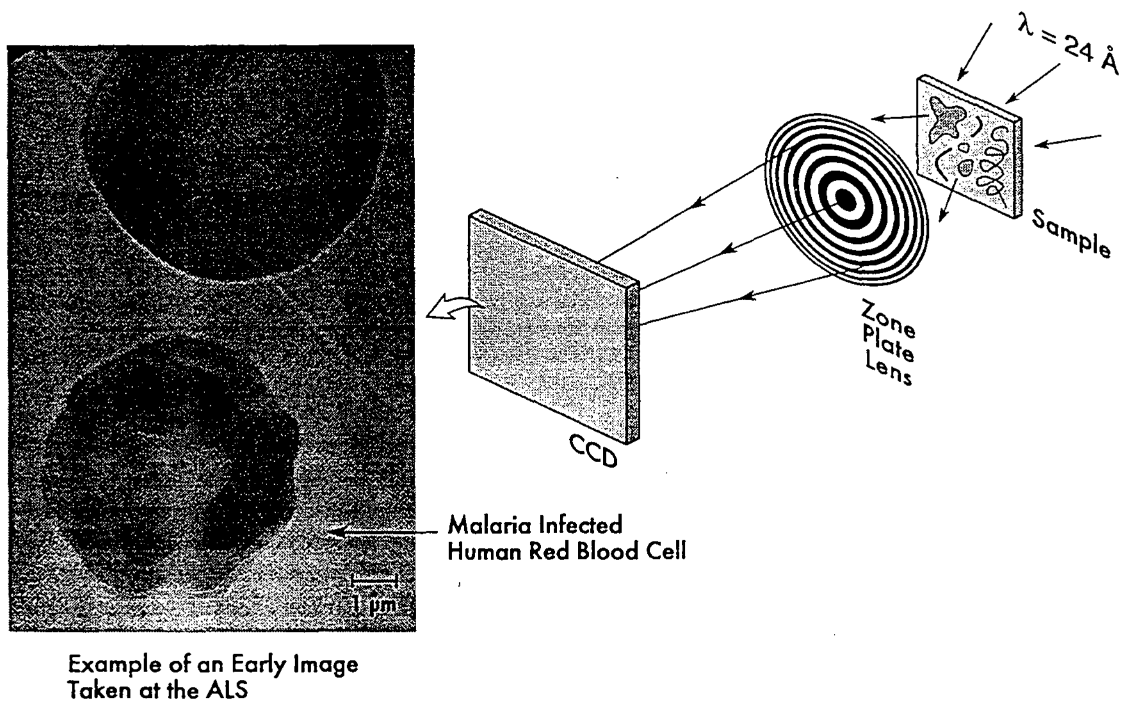

Figure 6. *This image of a malaria parasite (Plasmodium falciparum) within an intact human red blood cell is among the first to come from a transmission x-ray microscope at the Advanced Light Source. Such x-ray imaging promises resolution five times greater than that available with visible light, while offering the opportunity to image cells in aqueous environments without the extensive preparations required for electron microscopy. (Malaria research conducted by the Center for X-Ray Optics at Lawrence Berkeley National Laboratory.)*

Spectromicroscopy

High spectral and high spatial resolution can be combined for a powerful new tool: spectromicroscopy. One example of elemental imaging using spectromicroscopy is the study of plutonium using a small sample which is less radioactive than a household smoke detector (Figure 7).

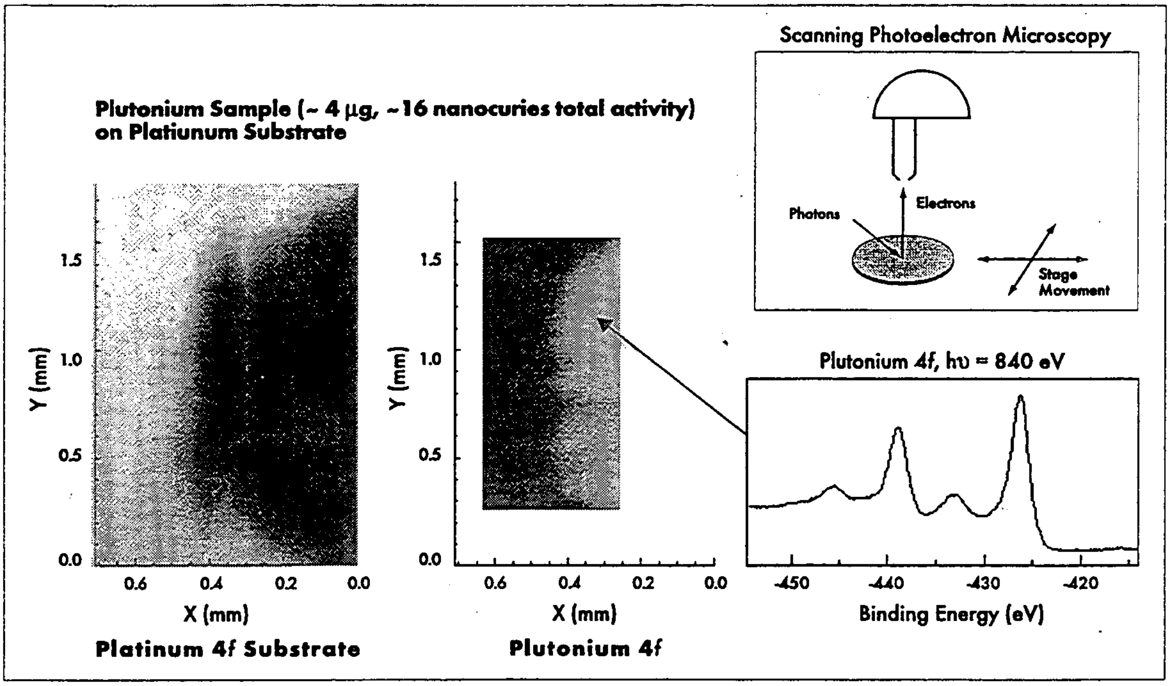

Figure 7. The power of combining spatial resolution and spectral resolution in spectromicroscopy is demonstrated in these data from a minute sample of plutonium. By imaging at photon energies corresponding to absorption edges for platinum and plutonium, researchers were able to locate an area of high plutonium concentration and take a photoelectron energy spectrum from that area. (Experiments performed at the Beamline 7.0 Spectromicroscopy Facility by researchers from the University of Wisconsin-Milwaukee, the University of Oregon, Lawrence Berkeley National Laboratory, and Lawrence Livermore National Laboratory.)

Uses of Synchrotron Radiation

The product of a synchrotron-radiation source is the light delivered to the hundreds of researchers who use the facility. In this age of intense international economic competition, it is certain that government and industrial sponsors of these facilities are relying on them to contribute to success in the global marketplace, whether through basic and applied research or by direct involvement in process development and production. Some areas where such contributions are expected include (figures cited represent estimated world-wide market values):

Semiconductors. Microcircuit chips for computers and electronic equipment are a $100 billion-per-year business. To continue the march toward ever more miniaturized devices, development of advanced technology—such as projection x-ray lithography for imprinting tiny circuit patterns on semiconductor chips—is required. Equally important are improved techniques for super-sensitive testing of semiconductor materials to detect trace amounts of damaging impurities.

Data storage. Magnetic computer-data storage is another multi-billion dollar market (estimated at $50 billion per year), but new magnetic materials capable of reading and writing each binary bit of information in a smaller area are needed to increase storage capacity at a rate matching the insatiable growth in demand.

Polymers. With annual sales in the $500 billion range, polymers represent a huge market for an amazing variety of products from the pedestrian to the most high tech. Petrochemical companies are constantly on the lookout for new materials with improved properties.

Pharmaceuticals. Manufacture of pharmaceuticals is a $150 billion-per-year industry. By studying the atomic structures of disease-causing agents and their target structures, it is possible to design pharmaceuticals with just the right molecular structure to block the action of viruses and other causes of disease ranging from the common cold to AIDS.

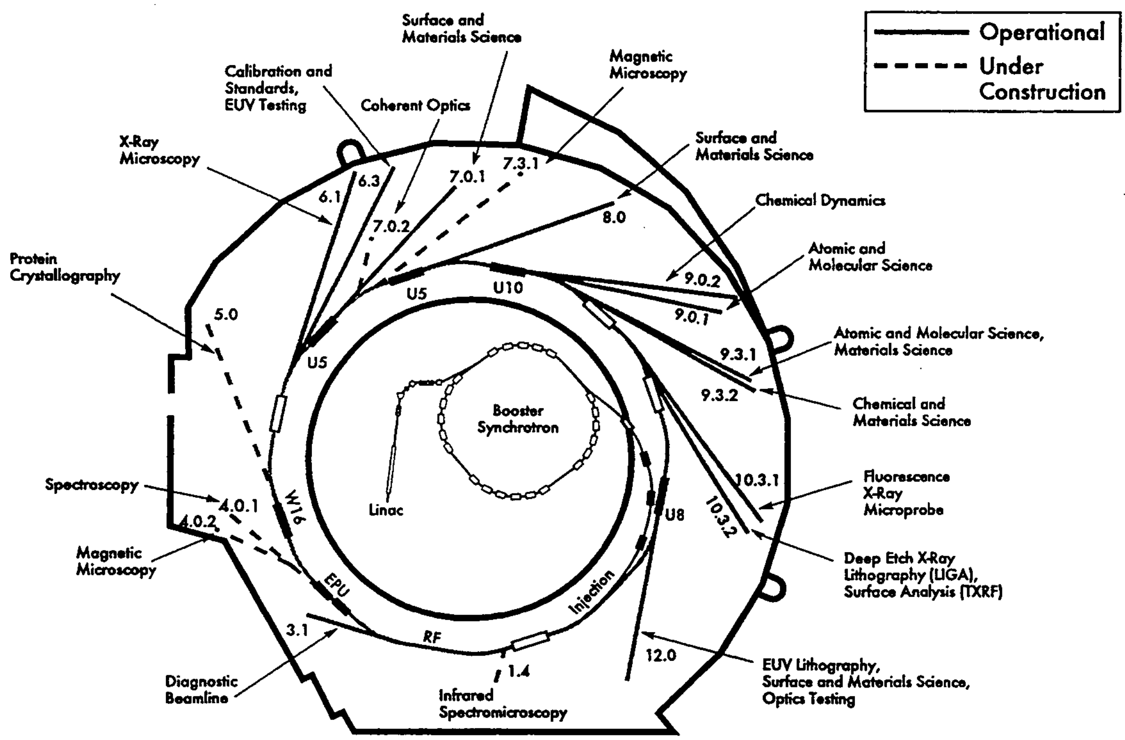

Figure 8. A plan view of the Advanced Light Source and its beamlines shows the wide range of fundamental and applied studies underway at that facility. Others will be developed as new capabilities and new needs arise.

Conclusion

A new generation of synchrotron light sources is producing extremely bright beams of vacuum-ultraviolet and x-ray radiation, powerful new tools for research in a wide variety of basic and applied sciences. Spectromicroscopy using high spectral and spatial resolution is a new way of seeing, offering many opportunities in the study of matter. Development of a new light source provides the country or region of the world in which the light source is located many new opportunities: a focal point for research in many scientific and technological areas, a means of upgrading the technology infrastructure of the country, a means of training students, and a potential service to industry. A light source for Southeast Asia would thus be a major resource for many years. Scientists and engineers from light sources around the world look forward to providing assistance to make this a reality in Southeast Asia.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76F00098.

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098