LBL--29465

DE91 004310

The Advanced Light Source at Lawrence Berkeley Laboratory—A High-Brightness Soft X-Ray Synchrotron-Radiation Facility

Alfred S. Schlachter and Arthur L. Robinson

Accelerator Fusion and Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

July 1990

Paper presented at the 15th International Conference on X-Ray and Inner-Shell Processes, Knoxville, Tennessee, July 9–13, 1990

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

THE ADVANCED LIGHT SOURCE AT LAWRENCE BERKELEY LABORATORY—
A HIGH-BRIGHTNESS SOFT X-RAY SYNCHROTRON-RADIATION FACILITY*

Alfred S. Schlachter and Arthur L. Robinson

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

ABSTRACT

The Advanced Light Source, a third-generation national synchrotron-radiation facility now under construction at the Lawrence Berkeley Laboratory, is scheduled to begin serving qualified users across a broad spectrum of research areas in the spring of 1993. Based on a low-emittance electron storage ring optimized to operate at 1.5 GeV, the ALS will have 10 long straight sections available for insertion devices (undulators and wigglers) and 24 high-quality bend-magnet ports. The short pulse width (30-50 ns) will be ideal for time-resolved measurements. Undulators will generate high-brightness soft x-ray and ultraviolet (XUV) radiation from below 10 eV to above 2 keV. Wigglers and bend magnets will extend the spectrum by generating high fluxes of hard x-rays to photon energies above 10 keV. The ALS will support an extensive research program in which XUV radiation is used to study matter in all its varied gaseous, liquid, and solid forms. The high brightness will open new areas of research in the materials sciences, such as spatially resolved spectroscopy (spectromicroscopy). Biological applications will include x-ray microscopy with element-specific sensitivity in the water window of the spectrum where water is much more transparent than protein. The ALS will be an excellent research tool for atomic physics and chemistry because the high flux will allow measurements to be made with tenuous gas-phase targets.

INTRODUCTION

The availability of intense, tunable, collimated, polarized radiation in the x-ray and ultraviolet (collectively, the XUV) regions of the spectrum has driven the evolutionary development of dedicated facilities optimized for the generation of synchrotron radiation.[1] The newest, third-generation synchrotron sources are based on the use of an electron or positron storage ring specifically designed to have very low emittance and several long straight sections containing insertion devices (wigglers and undulators).

The combination of a very-low-emittance storage ring with optimized undulators makes possible the generation of radiation with a spectral brightness that is a factor of 20 or more over that of existing, second-generation sources, depending on the spectral range. In the past, order-of-magnitude increases in brightness have led to qualitatively new developments in spectroscopic and structural studies of both gas-phase and condensed matter. The increased brightness of the third-generation synchrotron sources is expected to have a similar effect.[2,3]

Around the world, construction of several third-generation sources is either under way or planned. They include the Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory. The ALS is in its fourth year as a U.S. Department of Energy-funded construction project with a total estimated cost of $99.5 million. The project is scheduled to be completed in April 1993.

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

ACCELERATOR OVERVIEW

The ALS facility consists of an accelerator complex, a complement of insertion devices, beamlines, and associated experimental apparatus, and a building to house this equipment and to provide laboratory and office space. The ALS is described in detail in a conceptual design report.[4] All the performance data reported here are from *An ALS Handbook*.[5] A summary of the major parameters of the storage ring is given in Table I.

An overall layout of the facility's accelerator complex, which consists of a 50-MeV linac, a 1-Hz, 1.5-GeV booster synchrotron, and an electron storage ring, is shown in Fig. 1. Although the energy of the storage ring will range from 1 to 1.9 GeV, its performance is optimized at 1.5 GeV. Performance characteristics of the ALS are determined primarily by the design of the storage-ring magnet lattice. The ALS lattice has 12 long straight sections that are joined by 12 achromatic arcs, each containing three bending magnets. This structure is referred to as a triple-bend achromat (TBA). Each of the 12 identical segments (superperiods) of the ALS lattice also contains six quadrupole focusing magnets and four sextupole magnets.

The ALS produces electron beams that are bunched rather than continuous. The storage-ring rf system has a frequency of 500 MHz, so the spatial separation between bunches is 0.6 m and the temporal separation is 2 ns. The storage-ring lattice, the rf system, and the impedance of the vacuum-chamber hardware determine the length (spatial and temporal) of the bunches. For the ALS at the nominal current of 400 mA, the predicted full-width-at-half-maximum (FWHM) value of the bunch length is 35 ps. Fig. 2 shows the electron-bunch structure.

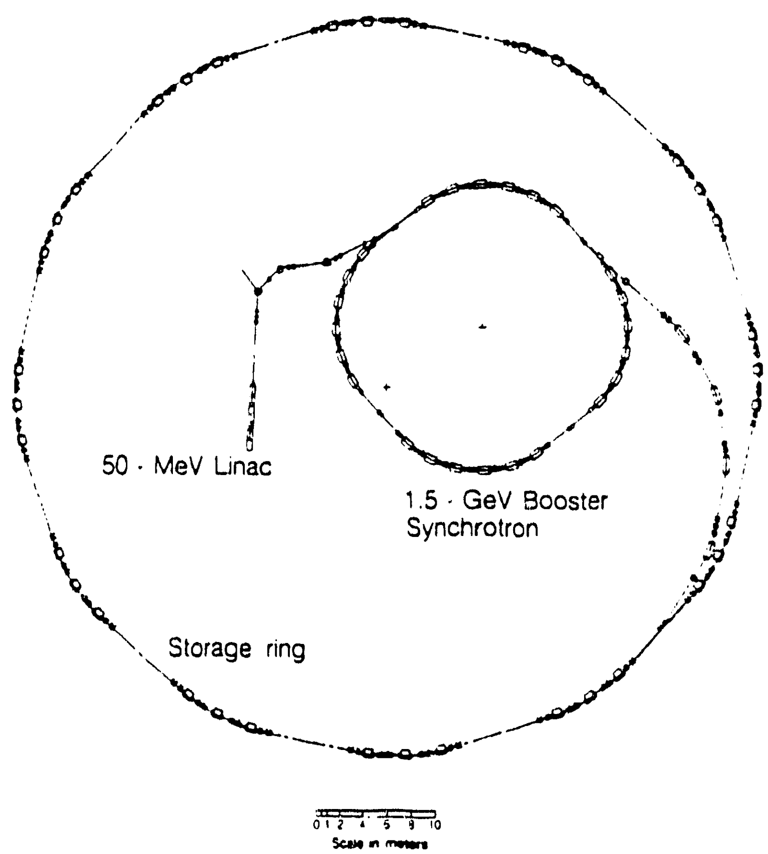

Fig. 1. Layout of the ALS accelerator complex showing the placement of the 50-MeV electron linear accelerator, the 1.5-GeV booster synchrotron, and the storage ring.

To avoid trapping positive ions in the potential well of the negatively charged electron beam, the multibunch mode with a 400-mA current will have 250 contiguous bunches, followed by a gap of 78 empty buckets. For particular experiments—for example, those involving time-of-flight measurements—it can be advantageous to have only one or a few circulating electron bunches in the storage ring. In the few-bunch mode, the nominal current per bunch will be 7.6 mA and the bunch length (FWHM) is predicted to be 55 ps, although still larger bunch currents may be tolerated (with additional bunch lengthening) before the beam becomes unstable.

Table I Main Parameters of the ALS Storage Ring

Beam energy [GeV]	
Nominal	1.5
Minimum	1.0
Maximum	1.9
Circumference [m]	196.8
Beam current [mA]	
Multibunch	400
Single bunch	7.6
Beam emittance, rms [m·rad]	
Horizontal	$<10^{-8}$
Vertical	$<10^{-9}$
Relative rms momentum spread	
Multibunch	8.0×10^{-4}
Single bunch	13.0×10^{-4}
Radiation loss per turn [keV]	91.5
Beam lifetime [h]	8
Nominal bunch duration, FWHM [ps]	30-50
Number of straight sections	12
Number available for insertion devices	10
Length available for insertion devices [m]	4.5

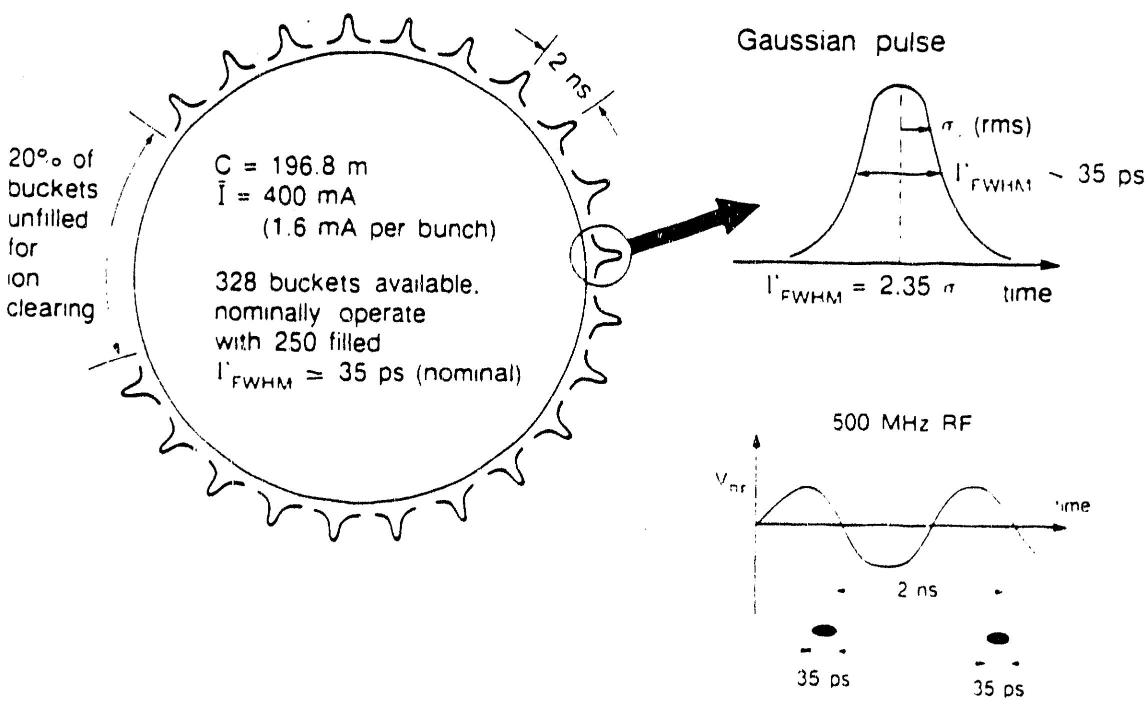

Fig. 2. Schematic illustration of the electron bunch structure in the ALS storage ring during multibunch operation. As shown at the upper right, each bunch has a full width at half maximum of about 35 ps. The spacing between bunches, dictated by the rf frequency, is 2 ns.

The ALS lattice is optimized for the use of insertion devices. The periodic magnetic field of an insertion device bends the electrons into an approximately sinusoidal trajectory in the horizontal plane, causing the emission of synchrotron radiation, as shown in Fig. 3. Of the 12 straight sections in the storage ring, one is used for injection and one is occupied by rf cavities, leaving 10 full straight sections available for undulators and wigglers up to 4.5 m in length. Operating at 1.5 GeV, the ALS is optimized for insertion-device operation in the XUV spectral regions.

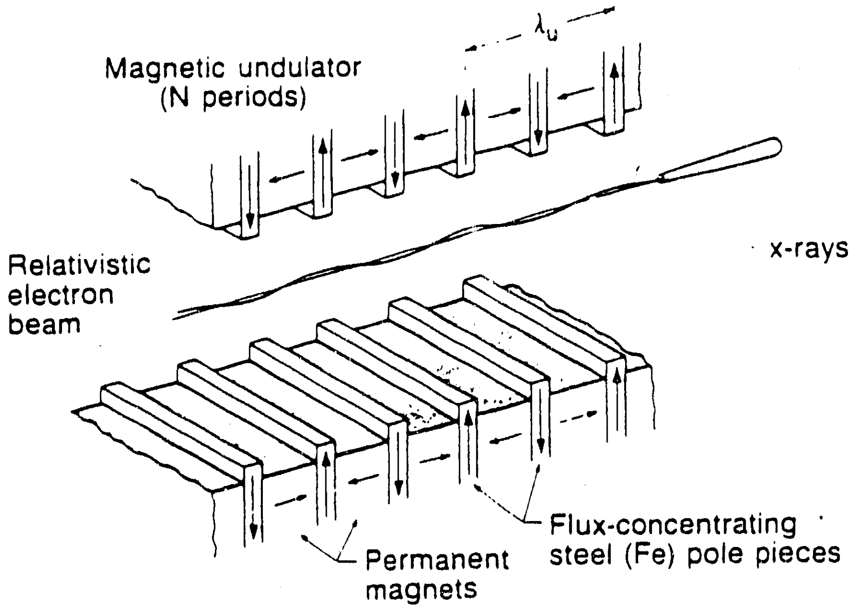

Fig. 3. Schematic drawing of the magnetic structure of an undulator with period λ_u and number of periods N. The oscillations of the electron beam passing through the structure produce XUV radiation of high spectral brightness

Based on the user requirements expressed in proposals received from prospective participating research teams, engineering designs are well under way for insertion devices that cover the ALS spectral range. The philosophy for the initial complement of insertion devices is to create a generic design and thereby reduce engineering and fabrication costs and enhance maintainability, as shown in Fig. 4. The goals of very high brightness and useful fifth-harmonic output impose unusually tight tolerances on the magnetic-field quality and thus on the mechanical structure of the undulators. Table II lists the properties of three undulators that span the soft x-ray and ultraviolet spectral regions when the ALS operates at 1.5 GeV and of a wiggler that extends spectral coverage into the hard x-ray region beyond 10 keV. Between them, the undulators will be able to excite the K shell of elements through silicon and the L shell of elements up to krypton, while the wiggler will be able to excite the L shell of nearly every element in the periodic table.

The spatial pattern of undulator radiation is a complex pattern of rings and lobes, but near the axis of an undulator, the spectrum of radiation consists of a series of narrow peaks, a fundamental and its harmonics. The spectrum at an observation angle θ is given by

$$\varepsilon_n[\text{keV}] = \frac{0.949 n E^2[\text{GeV}]}{\lambda_u[\text{cm}]}\left(\frac{1}{1 + K^2/2 + \gamma^2\theta^2}\right) \qquad (1)$$

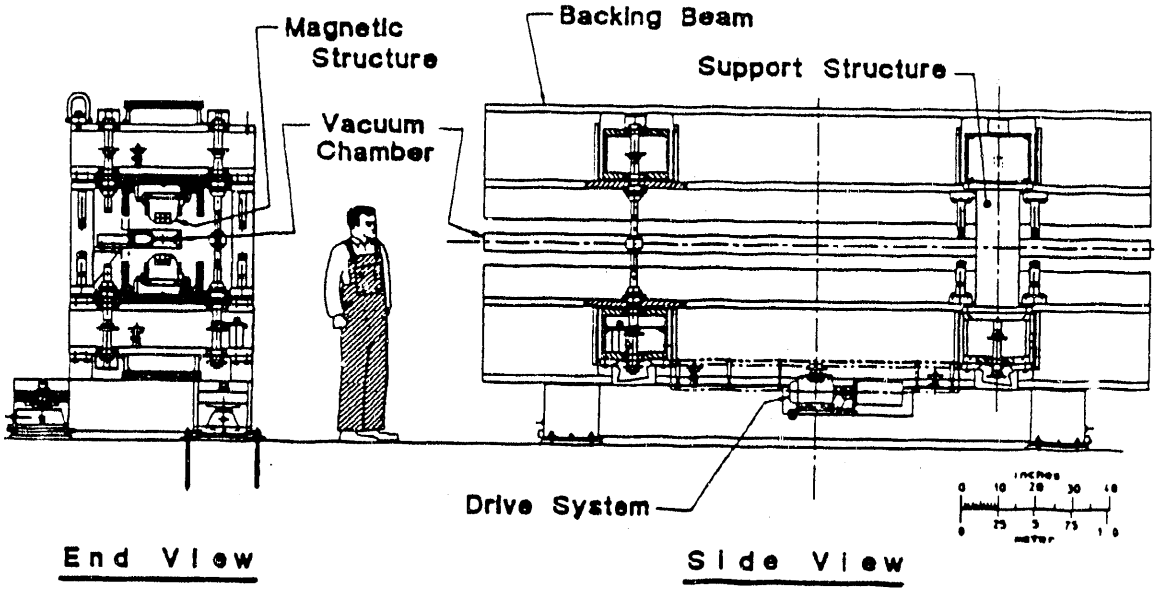

Fig. 4. Drawing of a generic insertion device for the straight sections of the ALS storage ring showing the main structural features that all undulators and wigglers will have in common.

Table II Parameters for Initial ALS Insertion Devices

Name	Period (cm)	No. of periods	Photon Energy range (eV)[a]	Critical energy (keV)
Undulators				
U8.0	8.0	55	5.4–220[b] [16.2–660] [27–1100]	–
U5.0	5.0	89	52–380 [156–1140] [260–1900]	–
U3.9	3.9	115	169–500 [507–1500] [845–2500]	–
Wiggler				
W13.6	13.6	16	–	3.1

[a]The photon energy range of the fundamental and of the third and fifth harmonics (shown in brackets) as the deflection parameter K decreases from its maximum value to approximately 0.5, when the electron-beam energy is 1.5 GeV.
[b]Below about 8 eV in the fundamental, the peak field in undulator U8.0 exceeds the bending-magnet field and may affect storage-ring operation.

where ε_n is the photon energy of the nth harmonic, E is the electron-beam energy, K is the deflection parameter, which is proportional to the undulator magnetic field and is usually about equal to 1, and λ_u is the period of the undulator. The relative bandwidth $\Delta\varepsilon/\varepsilon$ of each peak is approximately

$$\Delta\varepsilon/\varepsilon = 0.9/nN \tag{2}$$

where N is the number of periods. The angular divergence θ of the fundamental is approximately

$$\theta = 1/N^{1/2}\gamma \tag{3}$$

The spectral range of the undulator is scanned by varying the undulator magnetic field, which decreases as the gap between the poles of the undulator increases. Scanning from low to high photon energies is therefore accomplished by moving the gap from a minimum to a maximum distance. Both the minimum and the maximum are arbitrarily set by the drop off of the photon flux at low and high gap values, but are also subject to constraints such as the vertical diameter of the storage ring vacuum chamber. At the ALS, use of the third and fifth harmonics of the undulators is planned to extend their spectral range to higher photon energies than can be reached with the fundamental alone.

The wiggler, which operates with a high magnetic field and hence a K value much greater than 1, generates a broad continuous spectrum characterized by a critical photon energy ε_c, defined as the photon energy above which half the total power is radiated. At the high end of the broad wiggler spectrum, the flux drops rapidly but is still one-tenth of its maximum value at photon energies near $4\varepsilon_c$. With an ε_c of 3.1 keV, the ALS spectral range extends into the hard x-ray region near 10 keV. High-quality synchrotron radiation will be available from the 24 bend-magnet ports as well. The critical photon energy of the bend magnets is 1.56 keV.

The spectral brightness is the flux per unit area of the source and unit solid angle of the radiation cone. For many purposes, it is only the central cone of undulator radiation that experimenters use. The average spectral brightness $\mathcal{B}_n$ in the central cone of an undulator is approximately

$$\mathcal{B}_n\ [\text{photons/sec/mm}^2/\text{mrad}^2/0.1\%\ \text{BW}] = \frac{3.62 \times 10^{12}\ I[\text{Amp}]NQ_n(K)}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}} \tag{4}$$

where Σ_x and Σ_y are the RMS source sizes in x and y coordinates for a beam with a Gaussian density distribution, I is the electron-beam current, Q_n is a function of value ≤ 1 and $\Sigma_{x'}$ and $\Sigma_{y'}$ are the RMS cone opening angles (angular divergence). The source size (angular divergence) is obtained by adding in quadrature the size (divergence) of the electron beam and the source size (divergence) of a diffraction-limited photon beam.

Being the density of flux in phase space, brightness is a conserved quantity that cannot be improved by an optical system and therefore represents a true source characteristic. Spectral brightness is shown in Fig. 5 for the undulators and wiggler described in Table II, the ALS bending magnets, and for representative sources at other facilities. The spectral brightness of ALS undulators is shown in more detail in Fig. 6 for the fundamental and the third and fifth harmonics of the undulators. In general, there can be many prominent higher harmonics, especially for undulators operating at K values much greater than 1.

COHERENCE PROPERTIES

A significant fraction of the radiation from the ALS undulators is spatially coherent. The criterion for spatial coherence is that the product of the area of the light source and the solid angle into which it emits be no larger than the square of the wavelength of the light. Since this is the diffraction condition, spatially coherent light is also said to be diffraction-limited. In accordance with the diffraction condition, the electron-beam emittance ε sets the minimum wavelength at which all the radiation can be diffraction limited, according to the relation

$$\varepsilon = \lambda_{min}/4\pi \qquad (5)$$

Even at wavelengths below the minimum, part of the radiation remains diffraction limited, the fraction decreasing as the square of the wavelength. In addition, for practical optical systems, it is possible to use several radiation modes without significantly losing resolution[6], thereby increasing the effective fraction of coherent radiation.

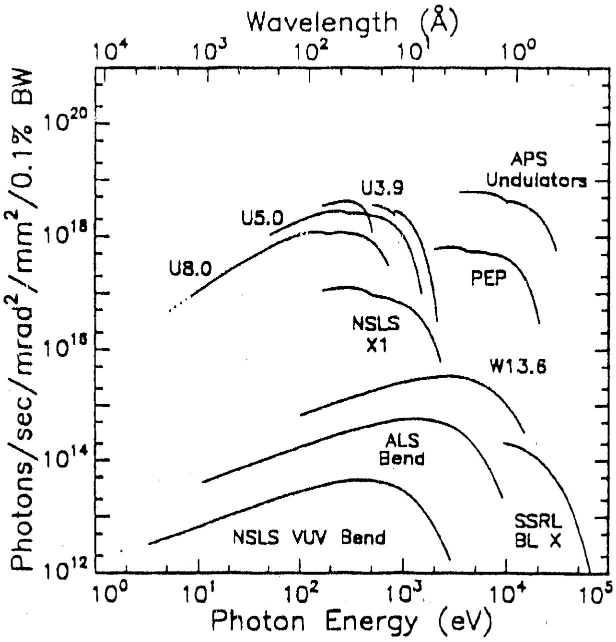

Fig. 5. Spectral brightness as a function of photon energy for the three undulators and one wiggler described in Table II, the ALS bending magnets, and representative sources at other facilities.

Although phase-sensitive techniques, such as holography, most naturally come to mind when thinking about coherent radiation, a more general virtue is the ability to focus. For example, a Fresnel zone plate can focus a coherent beam of soft x-rays to a spot whose radius is approximately 1.2 times the width of the outermost zone. With state-of-the-art microfabrication techniques, such as electron-beam holography, it is possible to make zone plates with outer zone widths of about 400 Å.[7] This capability can be exploited in scanning systems in which the focused x-ray beam sweeps across a sample to generate imaging or spatially resolved spectroscopic information with a comparable resolution.[8]

INSERTION-DEVICE BEAM LINES

Low-emittance storage rings and insertion devices have created new challenges for designers of UV and soft X-ray optics. The source size and divergence have become smaller. For ALS undulators at the high-photon-energy end of the spectral range, the size is typically 330 µm horizontal by 65 µm vertical and the divergence is typically 40 µrad horizontal by 30 µrad vertical. The small source size requires tighter tolerances for relay optics and monochromator components in both optical figure and finish to avoid loss of light (e.g., rms surface roughness ≈ 0.5 nm and tangential slope error <1 µrad for a condensing mirror). The attainment of higher resolution by use of smaller slits also becomes practical (the spectral-resolution goal of monochromators in undulator beamlines is $\Delta E/E \approx 10^{-4}$). Monochromator components therefore need tighter tolerances to avoid loss of resolution. Finally, the photon-beam power has increased to several kw/cm². The requirement that thermal distortions and stress be controlled complicates the design [e.g. water cooling in a UHV (≈ 1 ntorr) environment] and limits the choice of materials.

To meet these challenges, undulator beamlines are based on the spherical-grating monochromator system with water-cooled gratings. Depending on the beamline requirements, the condensing system chosen for ALS undulator beamlines consists of no, one, or two

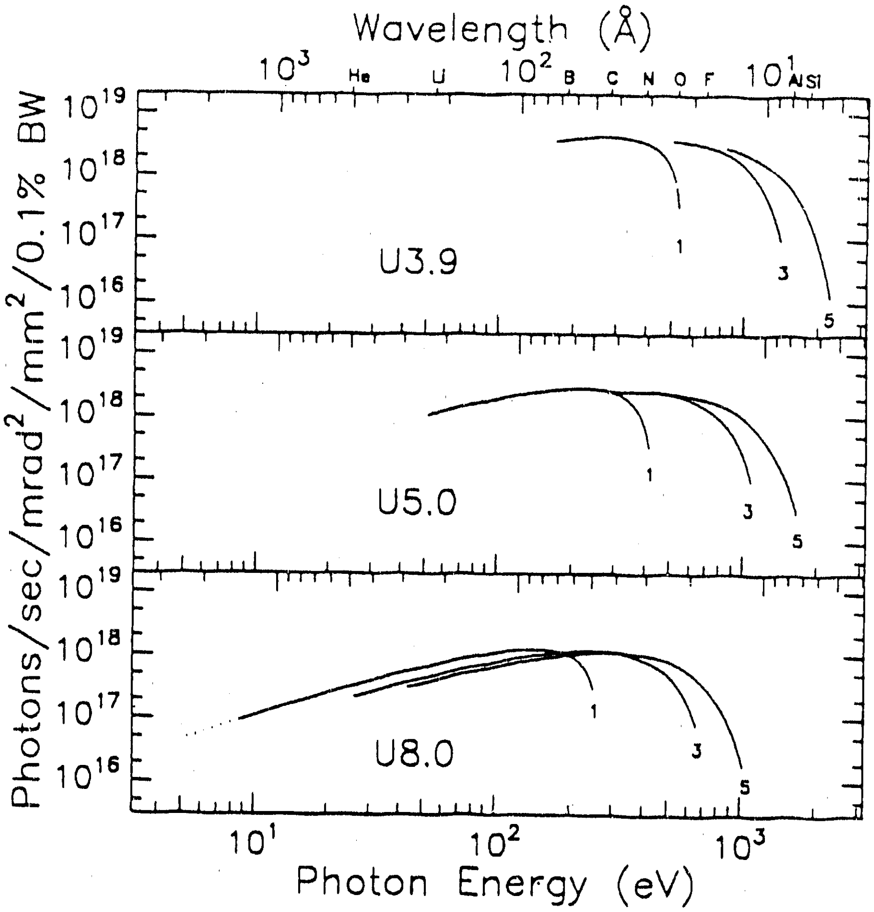

Fig. 6. Spectral brightness as a function of photon energy in more detail for the three undulators described in Table II. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap. Separate curves are shown for the first, third, and fifth harmonics of each undulator. The dotted extension of the first harmonic of U8.0 represents the performance when the undulator field exceeds the bend-magnet field, a condition that may affect storage-ring operation.

spherical mirrors. In the latter case, the mirror planes of incidence are perpendicular to each other in the configuration originated by Kirkpatrick and Baez in 1948. Each mirror has nearly zero focusing effect in its sagittal direction. Because of the low emittance of the ALS storage ring, the monochromator can accept the entire undulator beam in most cases, even at a slit-width of 10 μm.

SCIENTIFIC PROGRAM

The ALS is intended to be a national user facility that is open to all qualified scientists and technologists. Included in the scope of the ALS construction project is an experimental facilities budget for construction of an initial complement of insertion devices and insertion-device and bend-magnet beamlines. The primary responsibility for experimental apparatus (i.e., apparatus downstream from the exit slit of the monochromator) rests with the users; the responsibility for the design, fabrication, and operation of the beamlines will be shared between the ALS project and the users. Insertion devices will primarily be designed by the ALS project. Funding of subsequent insertion devices and beamlines is expected in future years from several sources, including private industry and federal agencies.

The method of implementing this strategy is the formation of participating research teams (PRTs) consisting of investigators with related research interests from one or more institutions. Each PRT will be assigned for its own research program, privileged access to the facilities it helps develop. The amount of access will depend on the resources (personnel, funding, and equipment) provided for the facilities by the PRT. However, a substantial fraction of the beam time at every beamline will be allocated to independent investigators by means of a proposal-review process.

Proposals were invited in March 1989 from PRTs to work with the ALS staff on the design, construction, and commissioning of insertion devices and beam lines, to develop the associated experimental apparatus, and to carry out the initial scientific program with these facilities. The initial insertion-device teams , selected in December 1989, are listed in Table III. Figure 7 shows a possible layout of the insertion devices and beamlines in the ALS building. Maximum beamline length is about 35 m.

Major research areas proposed for ALS undulator beamlines include: (1) soft x-ray microscopy of materials, surfaces, and biological systems, (2) spatially resolved spectroscopy (spectromicroscopy) of materials, surfaces, and biological systems, (3) high-resolution soft x-ray spectroscopy of materials and surfaces, (4) soft x-ray gas-phase spectroscopy of atoms and molecules, (5) molecular spectroscopy and dynamics with synchrotron radiation/laser pump-probe methods (6) spin-polarized photoemission spectroscopy. and (7) polarization-dependent experiments, such as circular dichroism of biological systems, which exploit the ability of undulators to generate radiation with a controlled polarization. X-ray microscopy and spectroscopy of biological systems in their natural state is possible because of a "water window" in the soft x-ray spectrum that allows the x-rays to penetrate the natural aqueous environment of these systems.

Wiggler-based x-ray studies will include: (1) spectroscopy of atoms in both the gas phase and in condensed matter when absorption edges lie at higher photon energies than can be reached with the undulators, (2) spatially-resolved elemental analysis with an x-ray microprobe, (3) grazing-incidence x-ray scattering from surfaces, and (4) x-ray diffraction of large biological molecules (protein crystallography).

Table III ALS Participating Research Teams

Insertion Device	Scientific Focus	Spokesperson
U10.0	Chemical Dynamics	Tomas Baer, U. of North Carolina
U8.0	Atoms, Molecules, Ions	Denise Caldwell, U. of Central Florida
U8.0	Pump-Probe, Timing, Dynamics Experiments	Victor Rehn, Naval Weapons Center
U5.0	Surfaces and Interfaces	Brian Tonner, U. of Wisconsin-Milwaukee
U5.0	Surfaces and Interfaces	Joachim Stöhr, IBM-Almaden
U3.9	X-ray Imaging and Optics for Life and Physical Sciences	Stephen Rothman, U. of California, San Francisco
W13.6	Atomic, Molecular, Optical Physics; Materials Science	Bernd Crasemann, U. of Oregon; Philip Ross, LBL
W13.6	Life Sciences	Alexandre Quintanilha, LBL

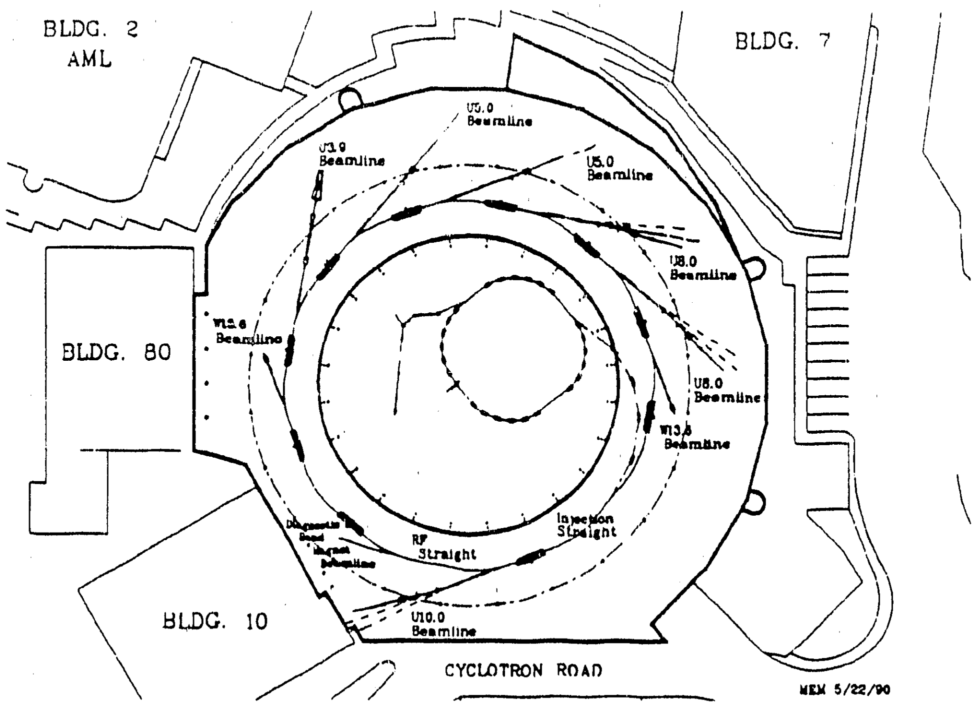

Fig. 7. Floor plan showing the placement of insertion devices and associated beamlines in the ALS building. The maximum beamline length is about 35 m. The bend-magnet ports are located in the center bend magnet of each storage-ring arc, two ports per magnet for a total of 24.

ACKNOWLEDGEMENTS

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Materials Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The contributions of the ALS staff to the publication *An ALS Handbook*, on which much of this report is based, are gratefully acknowledged.

REFERENCES

1. E.E. Koch, D.E. Eastman, and Y. Farge, in: *Handbook of Synchrotron Radiation*, ed., E.E. Koch (North-Holland, Amsterdam, 1983), pp. 1-64.
2. *Report of the Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source*, PUB-5154 (Lawrence Berkeley Laboratory, Berkeley, CA, 1985).
3. *Proceedings of the First Users Meeting for the Advanced Photon Source*, ANL/APS-CP-1 (Argonne National Laboratory, Argonne, IL, 1988).
4. *1-2 GeV Synchrotron Radiation Source*, PUB-5172 Rev. (Lawrence Berkeley Laboratory, Berkeley, CA, 1986). Note that the values of some ALS parameters have changed since the issuance of this report.
5. *An ALS Handbook*, PUB-643 Rev. 2 (Lawrence Berkeley Laboratory, Berkeley, CA 1989).
6. J. W. Goodman, *Statistical Optics* (Wiley, New York, 1985), p. 227.
7. Y. Vladimirsky, D. Kern, W. Meyer-Ilse, and D.T. Attwood, *Appl. Phys. Lett.* 54, 286 (1989).
8. H. Rarback et al., *Rev. Sci. Instrum.* **59**, 52 (1988).

END

DATE FILMED

12 / 13 / 90