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The Advanced Light Source: A New 1.5 GeV Synchrotron Radiation Facility at the Lawrence Berkeley Laboratory

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The Advanced Light Source: a new 1.5 GeV synchrotron radiation facility at the Lawrence Berkeley Laboratory

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The Advanced Light Source (ALS), now under construction at the Lawrence Berkeley Laboratory, is being planned as a national user facility for the production of high-brightness and partially coherent x-ray and ultraviolet synchrotron radiation. The ALS is based on a low-emittance electron storage ring optimized for operation at 1.5 GeV with insertion devices in 11 long straight sections and up to 48 bend-magnet ports. High-brightness photon beams, from less than 10 eV to more than 1 keV, will be produced by undulators, thereby providing many research opportunities in materials and surface science, biology, atomic physics and chemistry. Wigglers and bend magnets will provide high-flux, broad-band radiation at energies to 10 keV.

I. INTRODUCTION

The availability of intense, tunable, collimated, polarized radiation in the x-ray and ultraviolet 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 a very low emittance and several long straight sections containing insertion devices (wigglers and undulators).

The combination of a low-emittance storage ring with optimized undulators makes possible the generation of radiation with a spectral brightness that is increased by orders of magnitude over that of existing, second-generation sources. 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 synchrotron sources is either under way or planned, including the Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory. The ALS is in its third year of construction with a total estimated cost of approximately $100 million. The project is scheduled to be completed in April 1993.

II. THE ADVANCED LIGHT SOURCE

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. Details can be found in a conceptual design report and the ALS Handbook [4]. Table 1 reports some of the main features.

TABLE 1. Advanced Light Source machine design values.

Beam energy, nominal (GeV)	1.5
Beam energy range (GeV)	1.0-1.9
Maximum circulating current (mA)	400
Circumference (m)	197
Horizontal emittance, rms (m-rad)	10×10^{-9}
Number of straight section	12 (11 available)
Straight-section length available for insertion devices (m)	5
Bunch length, 2σ (ps)	28-47[a]
Beam lifetime (hr)	6

[a]Extreme values are for 250-bunch and single-bunch modes, respectively, at maximum current.

TABLE 2. Parameters for proposed ALS insertion devices.

Name	Period (cm)	No. of Periods	Photon Energy Range (eV)^a	Critical Energy(keV)
Undulators				
U8.0	8.0	61	8-240 [24-720, 40-1200]	-
U5.0	5.0	98	50-380 [160-1140, 260-1900]	-
U3.9	3.9	123	170-490 [510-1500, 850-2400]	-
Wiggler				
W13.6	13.6	16	-	3.1

^{a}The photon energy range of the fundamental and the third and fifth harmonic (shown in brackets) as the deflection parameter K decreases from its maximum value to 0.5.

The accelerator complex consists of a 50-MeV electron linear accelerator, a 1.5-GeV booster synchrotron, and an electron storage ring optimized to operate at 1.5 GeV, with the capability of spanning the range from 1 to 1.9 GeV. The layout is shown in Fig. 1. The storage ring design, based on a triple-bend achromat lattice, is designed to operate with a horizontal emittance of less than 10 nm-rad at 1.5 GeV. One super period of the lattice is shown in Fig. 2. The lattice has 12 straight sections, one of which is taken up by injection equipment and one of which is partially occupied by rf cavities. In the ten full straight sections, the length available for insertion devices is 5 m. In addition, there are 48 ports in the 36 dipole magnets of the lattice that can be used to extract bending-magnet radiation. In normal operation, the ring will be filled with 250 bunches that generate pulses of synchrotron radiation with a duration (2σ) of 28 ps at intervals of 2 ns. The electron bunch structure is shown in Fig. 3. For time-resolved experiments, it will be possible to operate in a few-bunch mode.

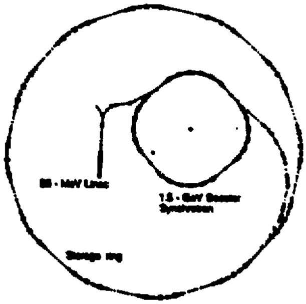

FIG. 1. Layout of the ALS accelerator complex showing the placement of the 50-MeV electron linear accelerator, the 1.5-GeV booster synchrotron, and the storage ring.

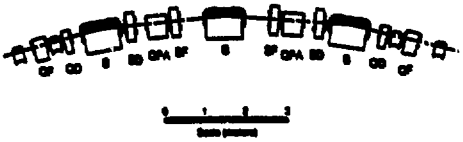

FIG. 2. One superperiod of the ALS triple-bend achromat lattice contains three combined-function (bending and focusing) magnets (B), six quadrupole focusing magnets (QF and QD), and four sextupole magnets (SF and SD).

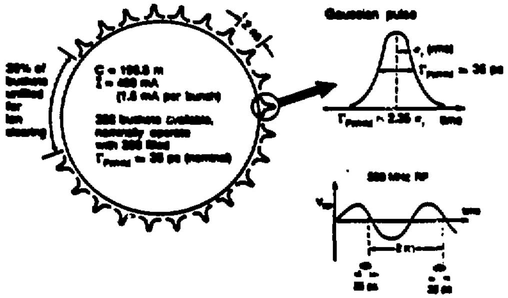

FIG. 3. Schematic illustration of the electron bunch structure in the ALS storage ring during multibunch operation. As shown at the upper right, each bunch has a full width at half maximum of about 35 ps. The spacing between bunches, dictated by the rf frequency, is 2 ns. (If rendered to scale, the illustration at the left would show 250 narrow spikes, disturbed around 80% of the ring's circumference.)

III. ALS RADIATION SOURCES

A proposed, initial complement of insertion devices consisting of several undulators will provide high-brightness photon beams from less than 10 eV to more than 1 keV. An undulator is made by use of a periodic magnetic structure, shown schematically in Fig. 4. A generic insertion device is shown in Fig. 5.

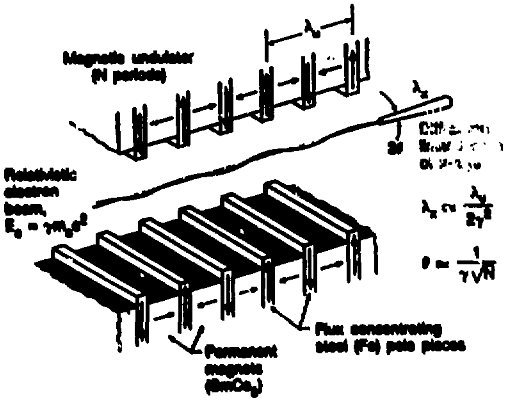

FIG. 4. Schematic drawing of a periodic magnet structure (an undulator) of period λ_u and with a number of periods, N. The oscillations of the electron beam passing through the structure produce ultraviolet and soft x-ray radiation (photons) of high spectral brightness.

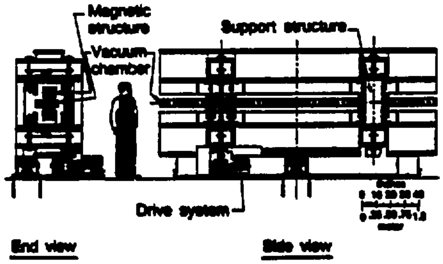

FIG. 5. Drawing of a generic insertion device for the straight sections of the ALS storage ring showing the main structural features that all undulators and wigglers will have in common.

The spatial pattern of undulator radiation is a complex pattern of rings and lobes, but on the axis of an undulator, the spectrum of radiation consists of a series of narrow peaks, a fundamental and its harmonics [4]

$$\varepsilon_n \text{ [keV]} = 0.950\, nE^2 \text{ [GeV]}/((1 + K^2/2))\lambda_u \text{ [cm]},$$

where ε_n is the photon energy of the nth harmonic, E is the photon energy, K is the deflection parameter (on the order of unity), which is proportional to the undulator magnetic field, and λ_u is the period of the undulator. The relative bandwidth of each peak is approximately

$$\Delta\varepsilon/\varepsilon = 1/nN$$

where N is the number of periods. In general, the spectral brightness of undulator radiation is also proportional to N^x, where x is between 1 and 2, depending on the ratio of the photon wavelength to the product of the size and divergence of the electron beam. These properties are summarized in Figs. 6 and 7.

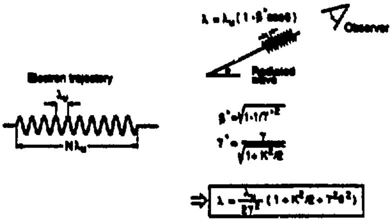

FIG. 6. Electron trajectory in an undulator, and undulator radiation observed.

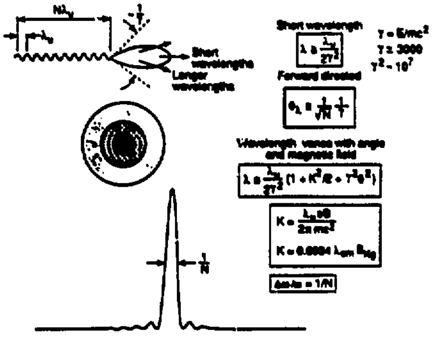

FIG. 7. Properties of undulator radiation, showing γ for 1.5 GeV electrons.

The spectral output 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 opening the gap from a minimum to a maximum distance, determined by the variation of the photon flux with gap and constraints such as the vertical dimension of the storage-ring vacuum chamber. An example is a U3.9 for 1.5 GeV electrons. The third harmonic of this undulator extends to higher photon energies (1.5 keV) than can be reached with the fundamental alone (0.5 keV); the fifth harmonic extends the range to 2.4 keV.

The photon energy range at ALS can be extended to 10 keV by use of a wiggler. For an electron energy of 1.5 GeV, a wiggler with a period of 13.6 cm has a critical photon energy ε_c of 3.1 keV, defined as the photon energy above and below 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 $4\varepsilon_c$, so that the ALS spectral range extends into the hard x-ray region near 10 keV, although the increased spectral range comes at the expense of a reduced brightness compared to that obtainable with undulators. By comparison, the critical photon energy of the bending magnets is 1.56 keV. Properties of an undulator and a wiggler are compared in Fig. 8. Figures 9 and 10 show the spectral brightness of radiation from three proposed undulators, the W13.6 wiggler, and the bend magnets [4].

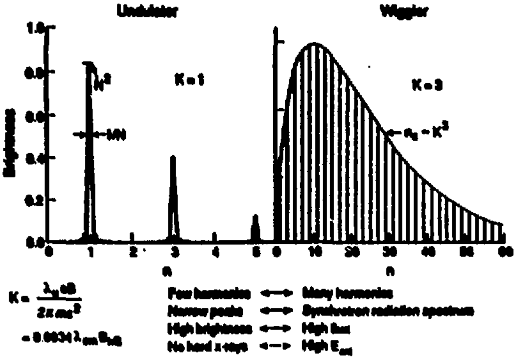

FIG. 8. Comparison of undulator and wiggler radiation.

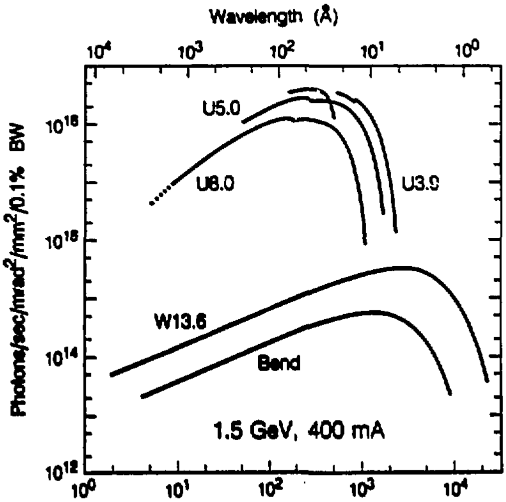

FIG. 9. Spectral brightness as a function of photon energy for proposed ALS undulators, wiggler, and bend magnet. Performance envelope for each insertion device is shown. This figure was calculated using $\varepsilon_x = 10^{-8}$ m-radian; effects of electron energy spread and undulator errors are relatively small on the scale of the figure and have not been included.

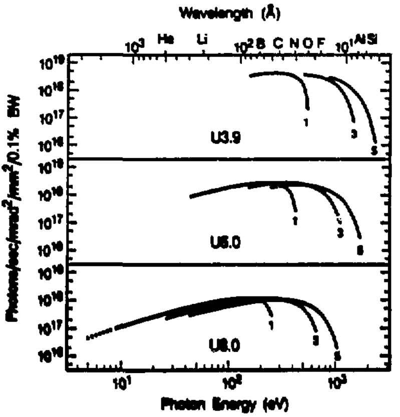

FIG. 10. Spectral brightness as a function of photon energy for proposed ALS undulators. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap. Performance envelopes for first, third, and fifth harmonics are shown, along with the K edges of various light elements. This figure was calculated using $\varepsilon_x = 10^{-8}$ m-radian; effects of electron energy spread and undulator errors are relatively small on the scale of the figure and have not been included.

IV. COHERENCE PROPERTIES

A potentially useful feature of ALS undulator radiation is its coherence properties. 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 micro-fabrication techniques, such as electron-beam lithography, it is possible to make zone plates with outer zone widths of about 400 Å [5]. 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 [6]. It is also possible to use zone plates as imaging lenses in an x-ray microscope.

V. ALS SCIENTIFIC PROGRAM

The ALS will be a national user facility that is open to all qualified scientists and technologists. Included in the scope of the ALS construction project is a budget for experimental facilities 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 of the exit slit of monochromator, rests with the users; the responsibility for design, fabrication and operation of the beamlines will be shared between the ALS project and the users. Insertion devices will be primarily designed, built, and paid for 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 consisting of investigators with related research interests from one or more institutions. Members of insertion-device teams and bending-magnet teams will receive preferential access to ALS beamtime in return for their efforts. Moreover, the selection of insertion devices and beamlines and their performance characteristics will depend on the needs of the user community. A substantial fraction of the beamtime at every beamline will be available to general users, based on a proposal-review process.

Letters of Interest have been received, and proposals have been solicited, from prospective groups interested in forming participating research teams. The letters received span a broad range of disciplines and experimental techniques. Based on these initial responses, research areas eventually expected to be represented at the ALS on 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) time-resolved measurements of processes at surfaces and interface, (5) electronic structure of actinide elements, (6) soft x-ray gas-phase spectroscopy of atoms and molecules, (7) molecular spectroscopy and dynamics with synchrotron radiation/laser pump-probe methods (8) spin-polarized photoemission spectroscopy, and possibly (9) polarization-dependent experiments, such as circular dichroism of biological systems, which exploit the ability of undulators to generate radiation with a controlled polarization.

Proposed wiggler-based x-ray studies include: (1) spectroscopy of atoms in both the gas phase and in condensed matter, including biological molecules, 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 of materials, minerals, and biological structures, (3) grazing-incidence x-ray scattering from surfaces, (4) surface microscopy and spectroscopy of minerals, and (5) x-ray diffraction of large biological molecules (protein crystallography).

Review of proposals for the first insertion devices and beamlines is expected to be completed by the end of 1989.

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