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Publication Date

1988-10-01



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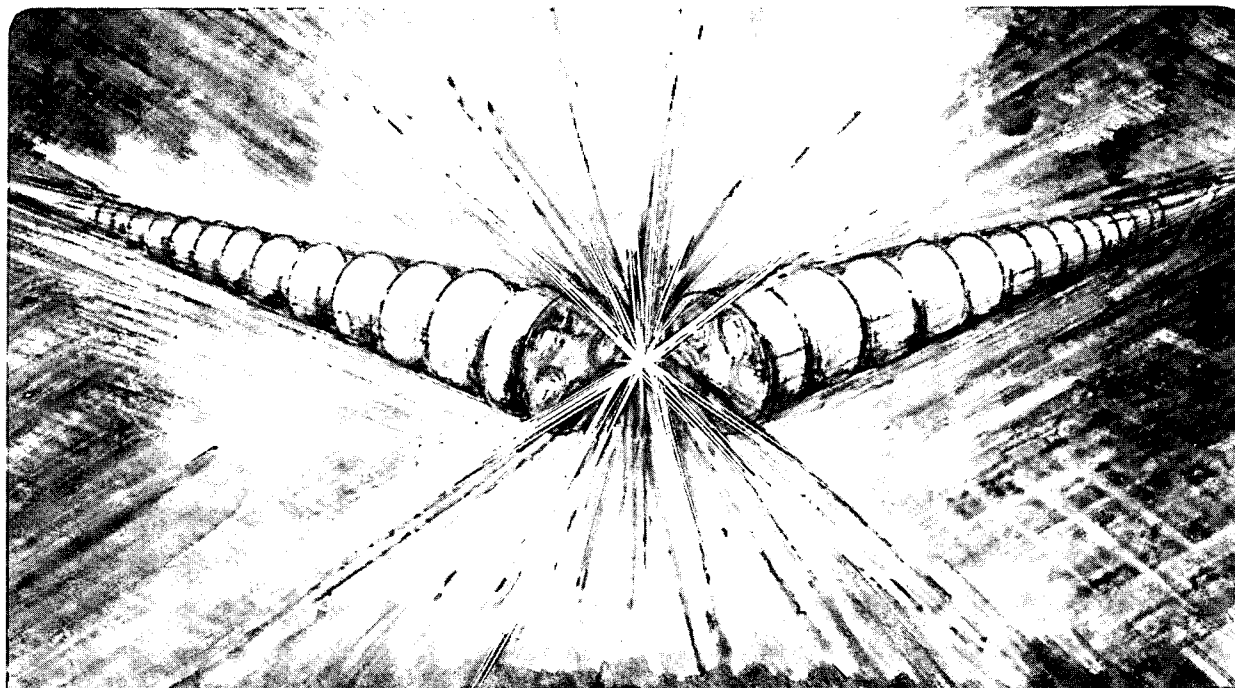
Accelerator & Fusion Research Division

Presented at the 10th International Conference on the
Application of Accelerators in Research & Industry,
Denton, Texas, November 7-9, 1988,
and to be published in the Proceedings

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October 1988



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Scientific Opportunities at the Advanced Light Source

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The Advanced Light Source (ALS) is a national user facility for the production of high-brightness and partially coherent x-ray and ultraviolet synchrotron radiation. Now under construction at the Lawrence Berkeley Laboratory with a projected completion date of September 1992, the ALS is based on a low-emittance electron storage ring optimized for operation at 1.5 GeV with insertion devices in eleven long straight sections. It will also have up to 48 bending-magnet ports. Scientific opportunities in materials science, surface science, chemistry, atomic and molecular physics, life science, and other fields are reflected in Letters of Interest received for the establishment of beamlines.

*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.

1. 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 a 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 (sometimes also called brilliance) that is increased by a factor of 1000 or more 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 entering its

third year as a U.S. Department of Energy-funded construction project with a total estimated cost (TEC) of \$98.7 million. The project is scheduled to be completed in September 1992.

2. The Advanced Light Source

The ALS facility consists of an accelerator complex, a complement of beamlines and associated experimental areas, and a building to house this equipment and to provide light laboratory and office space. Details are spelled out in a conceptual design report [4]. Table 1 reports some of the main features.

In summary, 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 but with the capability of spanning the range from 1 to 1.9 GeV. The storage ring design is based on a triple-bend achromat lattice and has a natural horizontal emittance of 3.4 nm-rad when operating at 1.5 GeV. 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 (nominally) 250 bunches that generate pulses of

synchrotron radiation with a duration (2σ) of 28 ps at intervals of 2ns. For time-resolved experiments, it will be possible to operate in a few-bunch mode.

3. ALS Radiation Sources

A strawman complement of insertion devices consisting of four undulators that span the spectral range available when the storage ring is operating at 1.5 GeV and a generic wiggler has been designed (Table 2). The spatial pattern of undulator radiation is a complex pattern of rings, but on the axis of an undulator, the spectrum of radiation consists of a series of narrow peaks, a fundamental and its harmonics [4]

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

where ϵ_n is the photon energy of the n th harmonic, E is the electron energy, K is the deflection parameter, 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

$$\Delta\epsilon/\epsilon = 1/nN$$

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..

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 arbitrarily set by the drop off of the photon flux at low and high gap values but also subject to constraints such as the vertical diameter of the storage ring vacuum chamber. At the ALS, it is planned to use the third harmonic of the undulators to extend their spectral range to higher photon energies (1.65 keV) than can be reached with the fundamental alone (0.55 keV), and there is some interest in using the fifth harmonic to extend the range still further.

The generic wiggler 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 $4\epsilon_c$, 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. By comparison, the critical photon energy of the bending magnets is 1.56 keV. Fig. 1 shows the spectral brightness of radiation from the four strawman undulators, the generic wiggler, and the bending magnets [4].

4. Coherence Properties

A feature of ALS undulator radiation that was not initially appreciated is its coherence properties. Consider

an electron beam with a gaussian density distribution and characterized by an emittance $\varepsilon = \pi\sigma\sigma'$, rms radius σ , and rms angular divergence σ' that acts as a source of radiation of diameter d with half-opening angle θ . Equating the phase space areas of the electron beam and that of diffraction-limited (spatially coherent) radiation, one arrives at the relation [5]

$$\varepsilon = \lambda_{eq}/4\pi,$$

where λ_{eq} is the shortest wavelength for which full spatial coherence can be obtained. Similarly, temporal (longitudinal) coherence is characterized by a coherence length [5]

$$l_c = \lambda^2/\Delta\lambda \approx nN\lambda.$$

Fig. 2 shows, the coherent power, defined as fully spatially coherent and with a coherence length of 1 μm , available throughout the spectral range of the ALS strawman undulators [4]. The characteristic $1/\varepsilon^3$ dependence of the coherent power at high photon energies occurs when the wavelength is less than λ_{eq} .

Although phase-sensitive techniques, such as holography, most naturally come to mind when thinking about coherent radiation, a more general virtue is that of focusability. 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 lithography, it is possible to make zone plates with outer zone widths of about 400 Å [6]. 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 [7]. It is also possible to use zone plates as imaging lenses in an x-ray microscope. Fig. 3 shows a soft x-ray image of a portion of an integrated circuit pattern obtained in this way that resolves features 700Å wide [6].

5. ALS 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 a trust fund of approximately \$20 million for an initial complement of insertion devices and insertion-device and bending-magnet beamlines. Instrumentation of the ALS is envisaged as a community project with the primary responsibility for experimental equipment resting with the users, the responsibility for the beamlines resting jointly with the Laboratory and the users, and the responsibility for the insertion devices resting primarily (but not exclusively) with the Laboratory. Funding of subsequent insertion devices and beamlines will come 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 mix of insertion devices and their performance characteristics that is selected for development at the ALS will depend on the needs of the user community as represented by the requirements of the insertion-device teams. However, a substantial fraction of the beamtime at every beamline will be available to general users who are not members of the participating research teams.

During the spring and summer of 1988, the Laboratory issued a Call for Letters of Interest from prospective groups interested in forming participating research teams. Reviewing of candidate Letters of Interest for the first beamlines will begin before the end of 1988.

Letters of Interest received so far span a broad range of disciplines and experimental techniques. Based on these initial responses, research areas expected to be represented at 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, linear, circular, and elliptical. 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 [8].

Although the ALS is optimized for the use of the high-brightness undulators, there is considerable interest in wigglers for a diverse range of studies, including (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). Finally, with a low-field "mini-wiggler" it is possible to generate comparatively large fluxes of infrared radiation, which can be used for vibrational spectroscopy of surfaces.

Many of these experiments can also be done with radiation from one of the much larger number of bending-magnets at the ALS. It is expected that these sources will be widely exploited for more routine experiments or for the development of techniques later to be used on an undulator beamline. Bending-magnet beamlines are usually easier to operate, and, in those cases where there is no benefit in using an undulator or wiggler, the bending-magnet is the preferred source.

Topical workshop reports that review scientific opportunities at the ALS in materials and interface science, surface science, chemistry, atomic and molecular physics, and life science is available from the author, as is information about submission of Letters of Interest.

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 author gratefully acknowledges the contributions of D.T. Attwood.

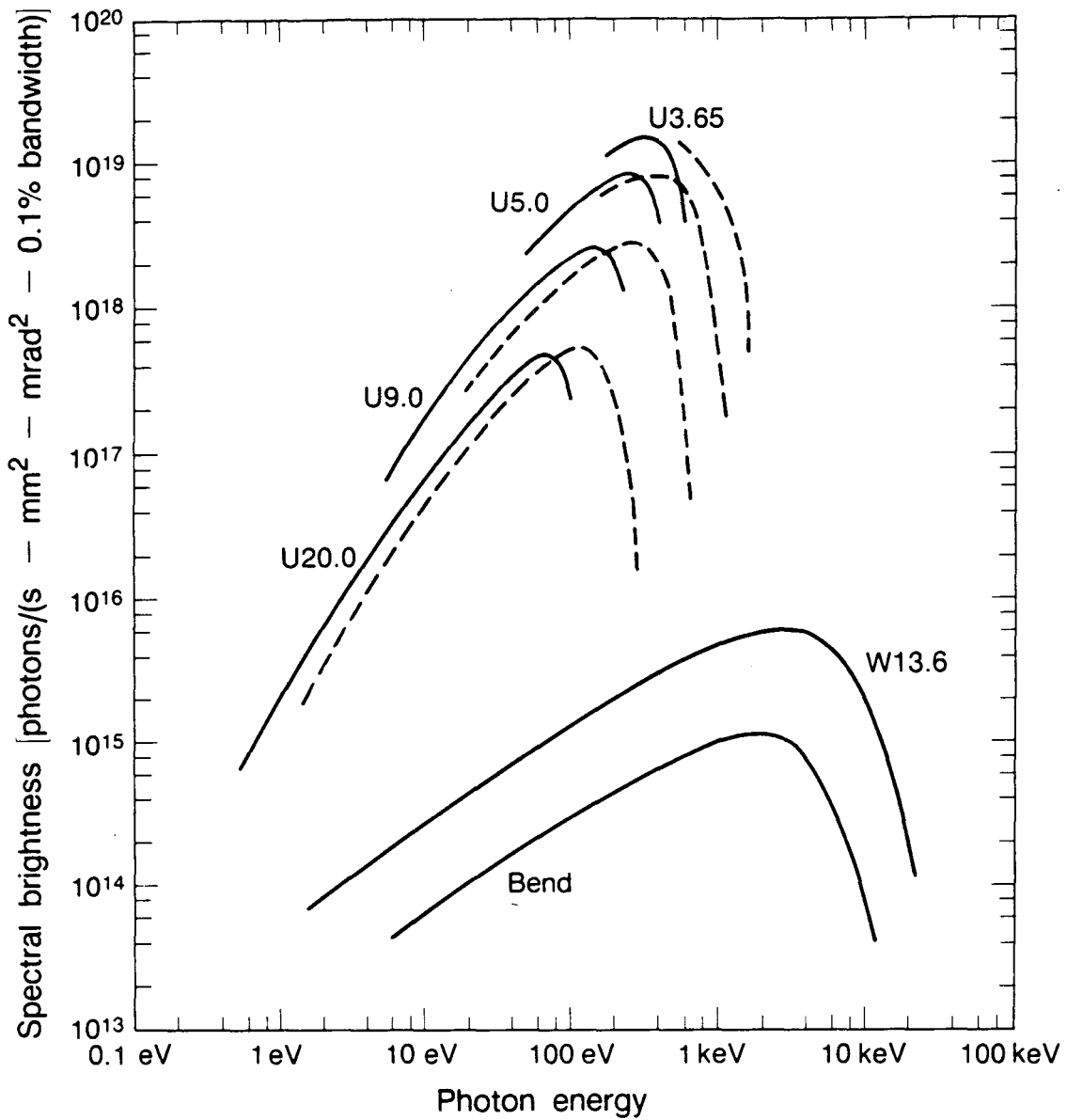
- [1] E.E. Koch, D.E. Eastman, and Y. Farge in Handbook of Synchrotron Radiation, ed., E.E. Koch (North-Holland, Amsterdam, 1983) pp 1-64.
- [2] Report of the Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source, PUB-5154 (Lawrence Berkeley Laboratory, Berkeley, CA, 1985).
- [3] Proceedings 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] D. Attwood, K. Halbach, and K.J. Kim, Science 228 (1985) 1265.
- [6] Y. Vladimirovsky, D. Kern, W. Meyer-Ilse, and D. Attwood, LBL-25738 (Lawrence Berkeley Laboratory, Berkeley, CA 1988), (submitted to Appl. Phys. Lett.).
- [7] H. Rarbach et al., Rev. Sci. Instrum. 59 (1988) 52.
- [8] S. Rothman et al., in: X-ray Microscopy II, ed. D. Sayre, M. Howells, J. Kirz and H. Rarbach (Springer, Heidelberg, 1988) pp. 372-377.

Fig. 1. Spectral brightness as a function of photon energy for the four undulators and the wiggler in Table 2 and of the bending magnets under the standard ALS operating conditions of beam energy 1.5 GeV and current 400 mA. For the undulators, the tuning range is shown for both the fundamental (solid lines) and the third harmonic (dashed lines). Each undulator curve is the locus of narrow radiation peaks that are tuned by altering the undulator gap.

Fig. 2. Average coherent power for the four undulators of Table 2. The fundamentals of each undulator are shown, together with the third harmonic of U3.65 under the standard ALS operating conditions.

Fig. 3. Soft x-ray image of a detail of the gate-level pattern associated with an experimental 0.1-micron MOSFET. The image, taken with 45-Å x-rays, shows a clearly resolved 700-Å gap between gold features [6].

Spectral Brightness of Radiation from the Light Source

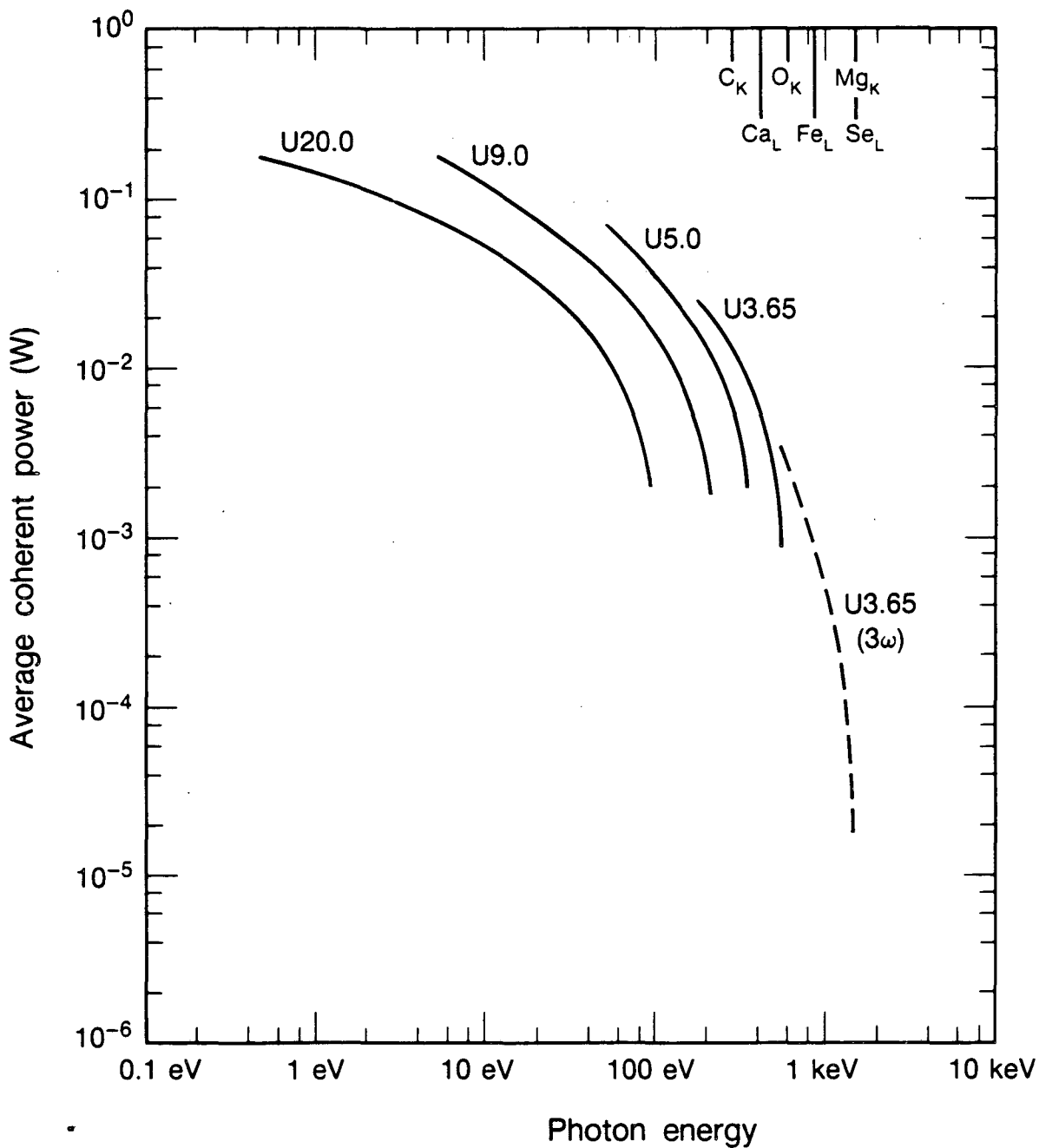


- For undulators, solid lines are the fundamental and the dashed lines are the third harmonic radiation.
- $E_e = 1.5 \text{ GeV}$, $I = 400 \text{ mA}$, $\epsilon_x = 4 \times 10^{-9} \text{ m-rad}$, $\epsilon_y = 4 \times 10^{-10} \text{ m-rad}$

XBL 867-9461A

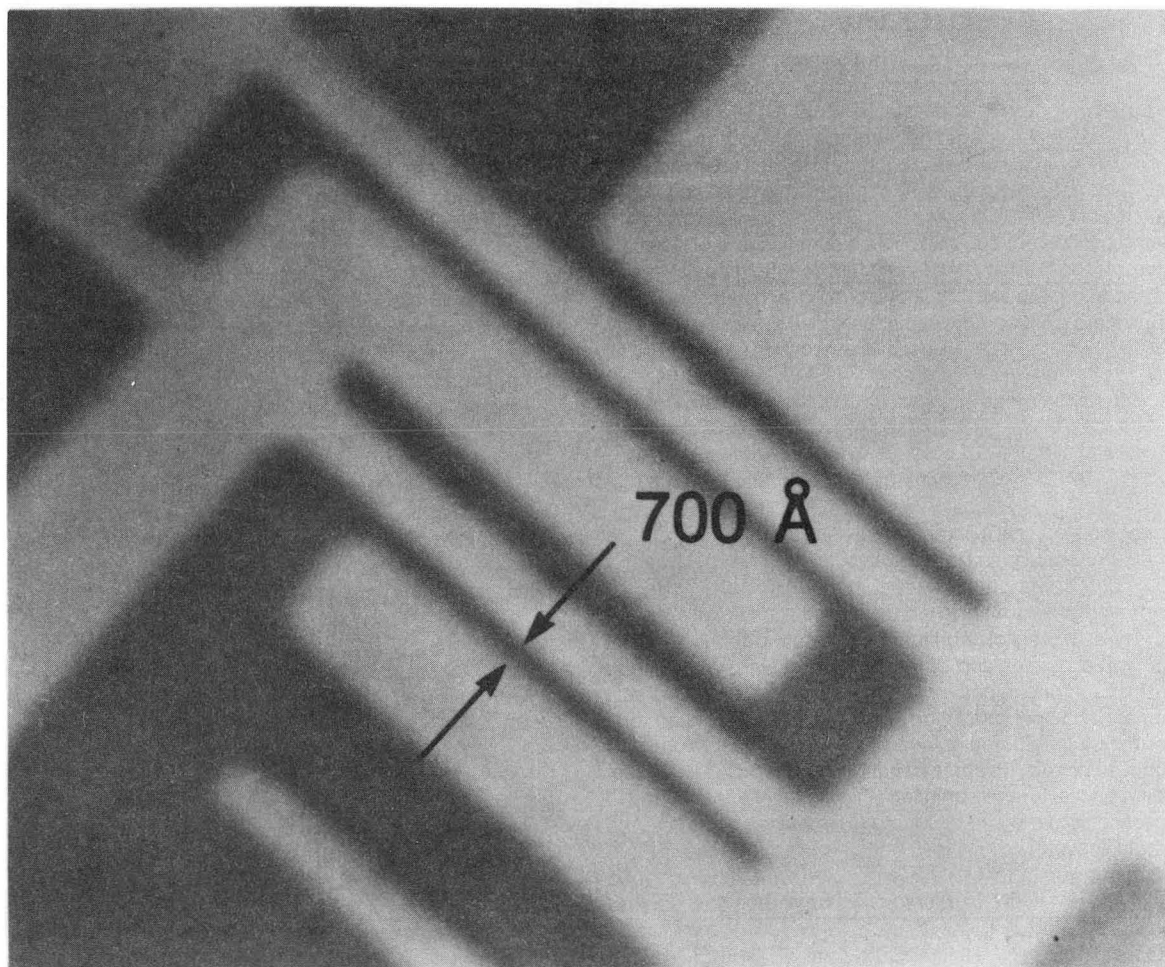
Figure 1

Coherent Radiation at X-ray and VUV Wavelengths



XBL 869-9823

Figure 2



XBB 884-2781 A

Figure 3

Table 1. Advanced Light Source machine design values.

| | |
|----------------------------------------------------------------|----------------------|
| Beam energy, nominal (GeV) | 1.5 |
| Energy range (GeV) | 1.0-1.9 |
| Average current (mA) | 400 |
| Horizontal emittance, rms (m-rad) | 3.4×10^{-9} |
| Number of straight sections | 12 |
| Straight section length available for insertion devices (m) | 5 |
| Bunch length, 2s (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 a selection of "strawman" ALS insertion devices.
The actual insertion devices will depend on user needs.

| Name | Period (cm) | No. of Periods | Photon Energy range (eV) ^a | Critical Energy (keV) |
|-------------------|-------------|----------------|---------------------------------------|-----------------------|
| Undulators | | | | |
| U20.0 | 20.0 | 23 | 0.5-95 [1.5-285] | - |
| U9.0 | 9.0 | 53 | 5-211 [15-633] | - |
| U5.0 | 5.0 | 98 | 50-380 [150-1140] | - |
| U3.65 | 3.65 | 134 | 183-550 [550-1650] | - |
| Wiggler | | | | |
| W13.6 | 13.6 | 16 | - | 3.1 |

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

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