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Report of the
ALS/SSRL Users Workshop

Lawrence Berkeley Laboratory
May 9-11, 1983

NATIONAL CENTER FOR ADVANCED MATERIALS

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Co-Chairmen

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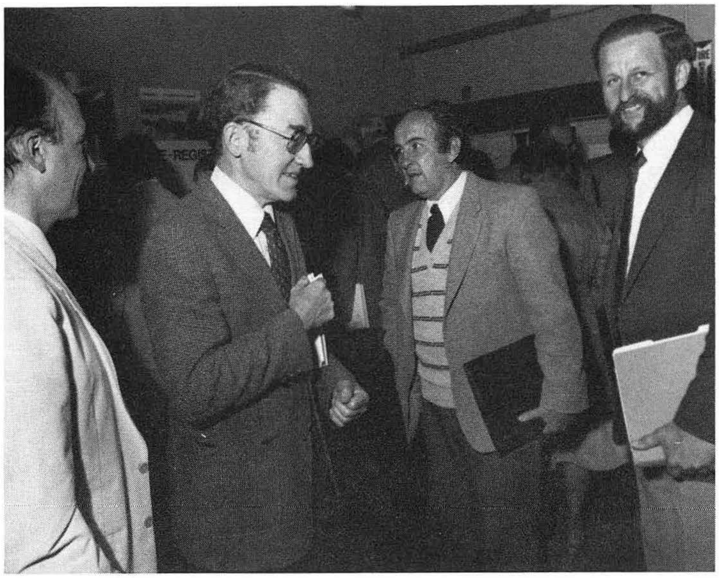
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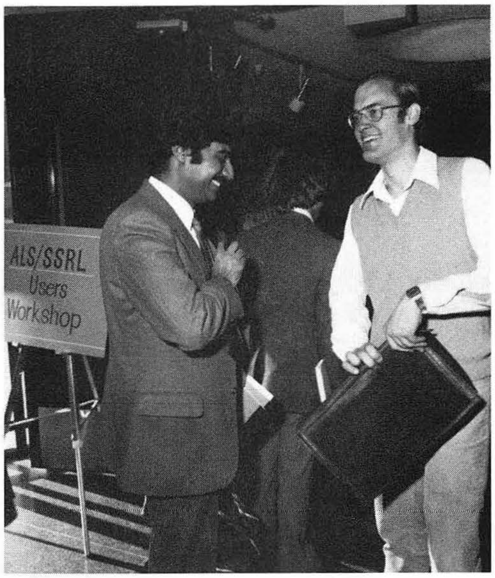
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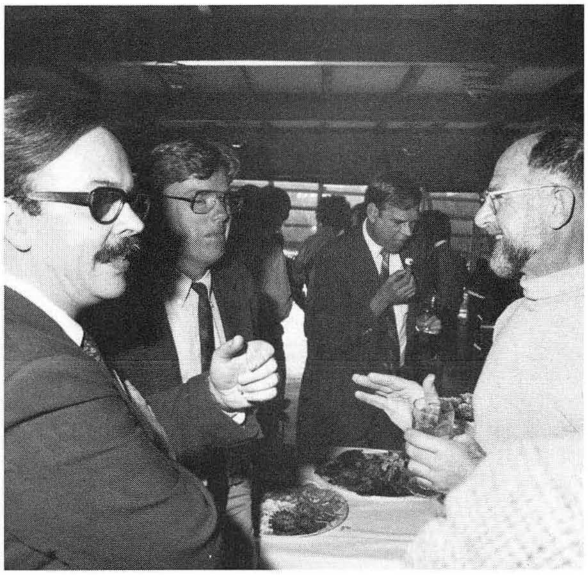

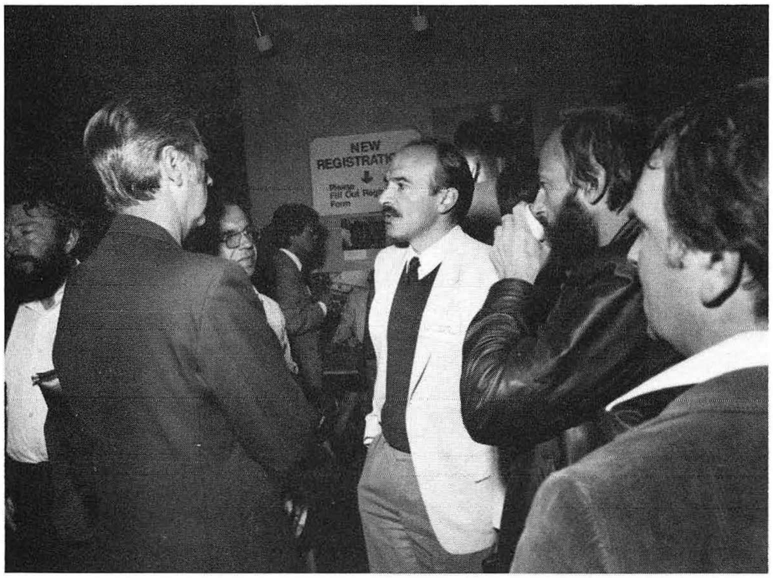
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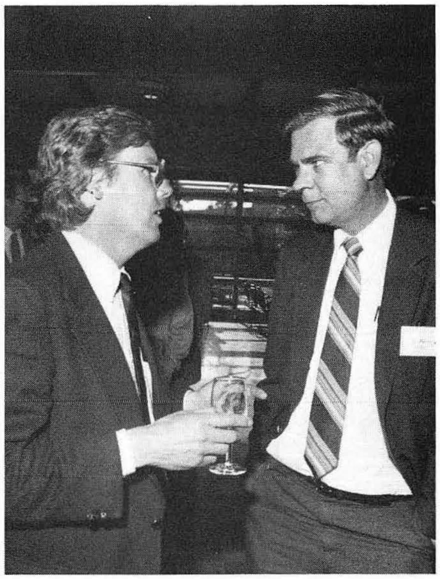

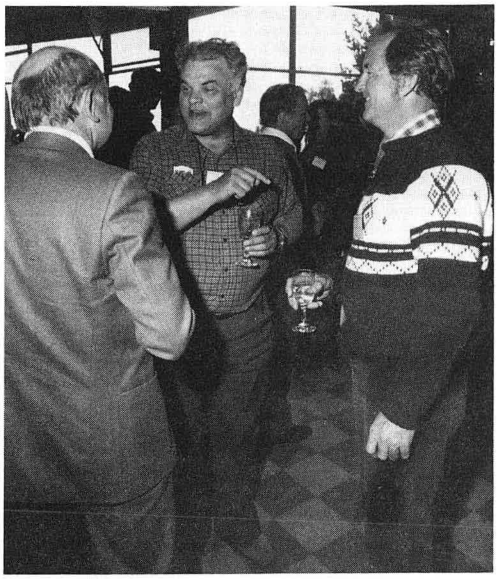

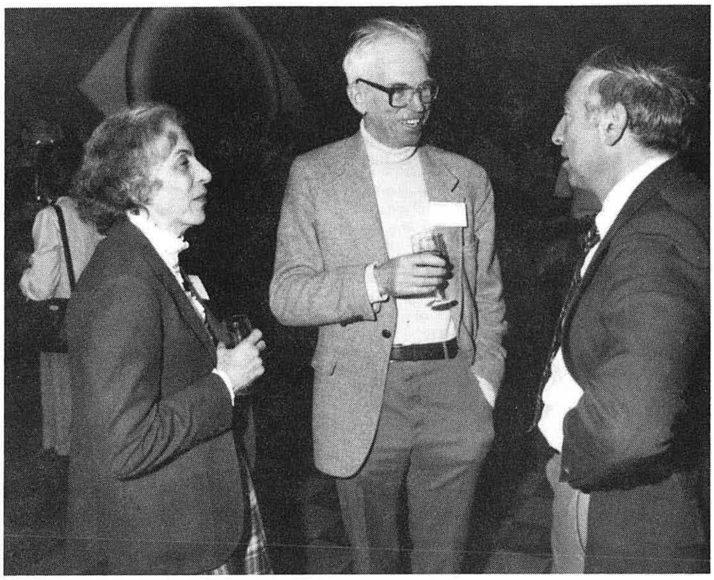

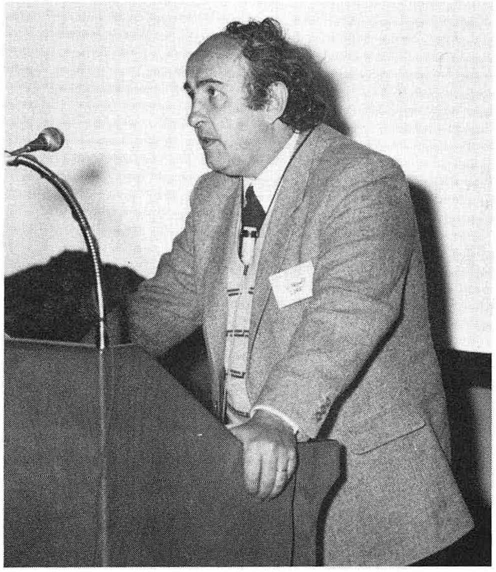

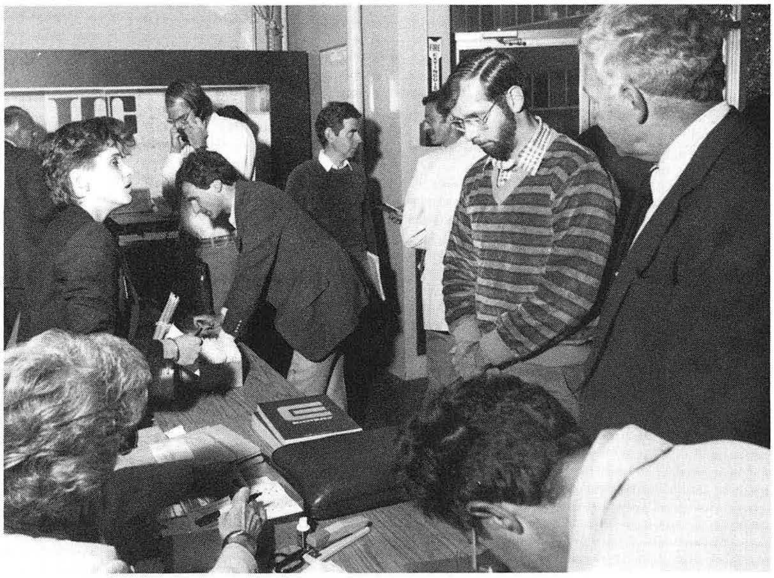

Preface

The ALS/SSRL Users Workshop was held May 9—11, 1983 at Lawrence Berkeley Laboratory. Its purpose was to focus on the science and the technical aspects (insertion devices, beam lines, and ancillary equipment) of the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory and the upgrade of Stanford Synchrotron Radiation Laboratory (SSRL). The ALS is a 1.3-GeV electron-storage ring designed to use insertion devices to produce extremely brilliant synchrotron radiation. Construction and operation of the ALS and improvements to SSRL are proposed as part of the National Center for Advanced Materials (NCAM).

Major sessions at the workshop dealt with the science, insertion devices, and beam-line design and components in the vacuum-ultraviolet, soft x-ray, and hard x-ray (specifically the SSRL upgrade) spectral regions. Special topics included free-electron lasers, physics and chemistry made possible by high spectral brilliance, and beam-line requirements for high-brilliance applications, such as x-ray imaging and lithography. Altogether 200 scientists and engineers attended, representing 17 universities, 19 private corporations, 7 national laboratories, 4 federal agencies, and 9 foreign countries. They met in six working groups charged with formulating recommendations to optimize the performance and usefulness of the ALS and the upgrade to SSRL. This publication includes the reports from each working group as well as a concise statement of summary recommendations.

Contents

1 Summary Recommendations

The ALS/SSRL Users Workshop was held at Lawrence Berkeley Laboratory, May 9—11, 1983 and focused on the science and certain technical aspects (insertion devices, beam lines, and ancillary equipment) of the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory and the hard x-ray upgrade proposed by Stanford Synchrotron Radiation Laboratory (SSRL). The workshop's 200 participants (Appendix 3) divided into six working groups charged with formulating recommendations on insertion devices and beam lines to be installed as part of the National Center for Advanced Materials project at the proposed ALS and at SSRL. These working groups focused respectively on the soft-x-ray, vacuum-ultraviolet (VUV), and hard x-ray spectral ranges, and on requirements for high-brilliance photochemistry, other high-brilliance applications, and free-electron lasers. The following chapters report the findings of the working groups. Here their major recommendations are summarized.

Two types of major recommendations emerged during the discussions. These can be classified as general recommendations—dealing with overall operations and support—and technical recommendations—pertinent to specific insertion devices, optical elements, and beam lines.

There were eight important general recommendations.

1) Assure, monitor and record beam parameters, especially stability.
2) Divide ALS running time between a "few-bunch" operating mode (e.g., for time-of-flight studies) and a "multibunch" mode (for normal operation to achieve maximum photon flux).
3) Make provisions for lasers to be synchronized with the ALS and used at many or all beam lines (e.g., provide adequate electrical power, electromagnetic shielding, timing signals for synchronization, and space for the lasers).
4) Provide abundant, skilled user support.
5) Provide users with office space, shop facilities, staging areas, preparation laboratories, and storage convenient to the ALS.
6) Supply experimental chambers suited for standard studies.
7) Operate all year.
8) Address visitors' needs for housing and parking.

Several technical recommendations were quite specific to individual working groups and are mentioned in the detailed report. However, the seven important technical recommendations iterated by two or more working groups are listed here.

1) Revise the initial complement of ALS beam lines to serve better the needs of VUV/soft x-ray experiments by adapting at least one of the undulators U_B and U_C to the energy range between 20 and 1500 eV. This revision additionally would simplify the requirements for

monochromators for these undulators.

2) Develop several bend-magnet beam lines for use by routine or time-consuming VUV/soft x-ray experiments.
3) Employ only one monochromator on each undulator beam line, with the photon beam illuminating one of two or three experimental chambers at the end of the line.
4) Include both an IR and a VUV free-electron laser in the ALS complex, to provide high-intensity, coherent radiation.
5) Defer selection of monochromators until newly developed types have been used and tested.
6) Develop new materials and designs for detectors and optical elements at NCAM's laboratories.
7) Pursue the hard x-ray upgrade for SSRL as proposed.

2 Report of the Working Group on Vacuum-Ultraviolet Beam Lines*

Introduction

The principal uses of vacuum ultraviolet and soft x-ray radiation from the ALS are expected to be the study of solids, surfaces, molecules, and atoms by various forms of photoelectron spectroscopy and by photostimulated desorption, and studies of the dynamics of molecules and molecular reactions using a combination of pulsed vacuum-ultraviolet radiation from the ALS and pulsed laser radiation. The new science was summarized nicely in the talks by Yves Petroff and Yuan Lee and we do not discuss it further, as it also has been described, in part, in the NCAM proposals.

We anticipate that two, or even three, beam lines will be necessary for each of these areas, with the materials studies requiring radiation over a very wide spectral range, 5 eV to at least 600 eV, and the dynamics studies requiring a more limited range, say 5–30 eV. The wide spectral range required for photoelectron spectroscopy may make the undulator U_A an inappropriate source, and it may be necessary to use wiggler W_E instead or to modify undulator U_B, keeping U_A for photochemistry. The tradeoff of wider spectral range for lower brightness will have to be considered carefully by users at the time of final design. We also feel that additional lines, perhaps of lesser quality, should be available for NCAM programmatic research that does not require exceptional brilliance or energy resolution. These lines could be located on bending magnets, and would in fact, provide quite intense radiation.

The remainder of this report deals with beam-line instrumentation and the storage ring itself, along with its operation. Ideally, special new optics, detectors, and materials will need to be developed to optimize the ALS' usefulness. The performance of beam lines at existing synchrotron sources may bear little relevance to the performance of ALS beam lines, even in the same spectral range. The very small angular spread of radiation from undulators, even at low photon energies, makes a *qualitative* difference in the way instrumentation will perform. Focusing by beam-line optics becomes better for small apertures, monochromator focusing is improved, and small-area gratings are adequate. The funding of NCAM appears to allow for research on

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*D.W. Lynch (Iowa State Univ., Ames Lab): Group Leader, F.C. Brown (Univ. of Illinois), C.H. Pruett (Physical Sciences Lab.), V.L. Rehn (Michelson Lab.), J.E. Rowe (Bell Labs), A. Sabersky (SAB Partners), N.V. Smith (Bell Labs), W.C. Walker (UCSB), R.S. Williams (UCLA) materials and components before they must be built, and this is an excellent opportunity to develop novel instrumentation.

Monochromators

The construction of an undulator- and wiggler-based synchrotron source, such the ALS, represents a unique opportunity to construct monochromators in the VUV (vacuum ultraviolet) spectral range with entirely new capabilities. This should include extension of the customary VUV range from 6–30 eV up to a larger value of 6–1000 eV so that considerable overlap will exist with the soft x-ray range. This extended range will allow more detailed study of photoelectron cross-section effects such as the Cooper-minimum phenomenon in Schottky-barrier studies of transition metal silicides, as well as the study of shallow core levels, such as the 2p levels of Mg, Al, Si, P, and S or the 4d levels of Cd, In, Sn, Sb, and Te. Thus high-resolution studies ($\lambda/\Delta\lambda \approx 10^4$) of both valence and core levels could be achieved in the same experiment. This combined approach would be particularly useful in surface studies where severe problems still exist in preparing samples that are sufficiently stable and with defect densities below $\sim 10^4$ cm^{-2}. In general one should use the high flux from the ALS to obtain high resolution of $\Delta E \sim 10$ meV. Recent studies by S. Kevan in the USA, A. Goldman in Germany, and others indicate that the natural line width of photoemission spectral features is about 20–30 meV instead of 200–300 meV as suggested by earlier low-resolution studies.

The working group also suggested that a synergistic approach to new beam-line technology should be explored whereby novel items such as specially ruled gratings and/or contamination-free mirror coatings are developed within NCAM by the Advanced Materials Synthesis Laboratory (AMSL) and the Advanced Device Concepts Laboratory (ADCL). Such a collaborative effort is now under way in several European and Japanese synchrotron radiation centers, such as BESSY in Berlin. One should also explore the use of synchrotron-based x-ray lithography to fabricate high-resolution gratings and Fresnel zone plates. Since lithography may be a part of the NCAM research program, an early start in applications to beam-line optics is recommended.

It is anticipated that new operational limits of photon flux and resolution in the VUV range will be achieved through the use of novel monochromator designs that exploit the unique collimation properties ($\Delta\theta_H \lesssim 0.25$ mrad, rather than 25 mrad) and have more accurate focusing with higher resolution. For example the toroidal grating monochromator (TGM), which is now routinely used as a medium-resolution ($\lambda/\Delta\lambda \sim 10^{+3}$) instrument, will become a higher-resolution ($\lambda/\Delta\lambda \sim 10^{+4}$) instrument with ~100 times smaller angle of emittance into the monochromator. Other new designs such as the proposed cylindrical, exponentially-ruled grating monochromator of Aspnes* should be built, since their capabilities will match well the small emittance of the ALS. Finally, it is possible to simplify more conventional designs, such as Seya-Namioka monochromators and other Rowland circle monochromators, e.g., the extended-range grasshopper (ERG) monochromator, so that better resolution and throughput are achieved. All of these suggestions point to the VUV area as having a variety of different types of somewhat special-function monochromators rather than a single, multiple-function, general-purpose monochromator. This will allow the development of a wide variety of new high-resolution, time-resolved, and laser-excited spectroscopies that promise to reveal important new spectral and dynamic interaction parameters of advanced materials.

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*D.E. Aspnes, J. Opt. Soc. Am. *72*, 1056 (1982).

Vacuum ultraviolet monochromators naturally fall into three general categories:

a) 10 to ~1000 eV – wide-range monochromators for high resolution and high flux, used for photoemission, photostimulated desorption, and other applications.

b) 5 to 30 eV – high resolution plus highest intensity monochromators for photochemistry and other excitation studies.

c) 5 to 12.5 or 30 eV – moderate resolution for NCAM programmatic materials research.

The differences in these categories will be brought out in the following discussion.

The different beam lines tend to be similar in the way that the monochromators are matched to the ALS so as to take maximum advantage of the intensity and collimation of insertion-device sources. It would be desirable, for example, to develop similar modular elements as first-surface mirrors. These might be diamond-turned metal mirrors in vacuum with cooling stems or straps. Thermoelectric cooling/heating devices have proved to be very reliable for maintaining the critical first surfaces at a stable temperature above ambient. Silicon carbide is also a possible first-surface material. These first mirrors would deflect at sufficiently great angles to filter the higher energies, as well as to separate beam lines in some cases. Higher orders will be a definite problem on the wigglers and also on undulators operating at sufficiently high K, so some means of pre-dispersing or simple filtering will be important. Finally, it is desirable to have standard microprocessor-based controllers for these and other monochromators at the ALS.

The design of a beam line should be carried out by one person or one group, designing from the source through the monochromator, and possibly through to the sample. Split responsibilities can lead to an inferior line. Modular elements, discussed above, are desirable, but *not* at the cost of a poorly matched beam line.

The wide range (10 – ~1000 eV) monochromators should be capable of high resolution ($\lambda/\Delta\lambda \sim 10^4$) *and* good flux. To achieve this resolution, monochromators with an entrance slit will be required, and will probably be used at rather small slit widths, e.g., 10 μm. This arrangement requires focusing optics that demagnify of the order of about 1:0.03. After the monochromator a highly focused beam with small spot size (0.1 × 0.1 mm) on the sample is desirable. These are likely to be the "work-horse" instruments so several (perhaps up to three) should be contemplated. These beam lines will serve many experimental programs, such as studies based on photoemission from solids, surfaces, and overlayers. The technique probes valence electrons and core electrons, using angle-resolved photoemission with moderate energy resolution, or sometimes high energy resolution, and high angle resolution for band-structure studies and adsorbate geometry studies by, e.g., photoelectron diffraction. Spin-polarized angle-resolved photoemission may also be carried out. These instruments also will serve for photon-stimulated desorption of ions (and neutrals). TGM (toroidal grating), Rowland circle (grasshopper), and plane mirror/plane grating geometries should be considered. It seems desirable to include a mixture of types. The TGM resolution will be improved with smaller gratings and high collimation, but such instruments require three separate gratings and a grating-change mechanism in order to cover the entire range. The grasshopper can cover the wide range with two or more gratings but special means will have to be taken to suppress higher orders at long wavelengths. There are in fact several ways to do this. It must be recognized that the selection of a monochromator with no entrance slit places the burden of achieving high resolution completely on the storage ring designers and builders. We point out that the ALS design beam height is not much smaller than that at NSLS-UV, so higher resolution without an entrance slit is not expected.

Note that one or more of the instruments listed in this section may be viewed as extended-range soft x-ray monochromators discussed in the report of the soft x-ray group. The location of wide-range monochromators is discussed at the end of this section.

The high-resolution monochromators will be especially important for photochemical and Rydberg excitation studies in the 5 to 30 eV range. (The lower limit of 5 eV is important for overlap with dye lasers.) Studies of molecular gases will require the highest resolution *and* intensity, especially where excitation lifetimes are measured and configuration-coordinate details sorted out. Resolution, $\lambda/\Delta\lambda$, as high as 10^{+4}, or better, will be desirable. This probably means coupling to a long (e.g. 3 m), normal-incidence, UHV-compatible monochromator. Undulator U_A would be a good source. This beam line probably will be addressed by the high-brilliance photochemistry group. A second monochromator of this type could be mounted on U_A with a deflecting mirror to illuminate it. Only one monochromator on U_A could operate at any one time, however.

For use in programmatic research by groups in NCAM, there probably should be from one to three beam lines serving the spectral range between 5 and 12.5 or 30 eV. The required number will depend completely on the development of NCAM. The upper energy limit of one such instrument could be set by the lithium-fluoride cutoff. This would permit operation of the monochromator in one atmosphere of dry nitrogen with great simplification in mechanical design and mechanism. Radiation would be focused through a LiF window (CaF_2 or high purity silica may be better from the point of view of radiation damage) by the first surface mirror (in vacuum) onto the entrance slit of the monochromator. The other monochromators of this class would be UHV instruments, e.g., a UHV Seya. At least one, if not all, of these monochromators might be a double-grating instrument for high spectral purity. Small f number is not required, so gratings, optical path, etc. can be relatively compact. These beam lines could be built on bending magnets. These sources would provide radiation fluxes comparable to or better than those obtainable on bending magnets at other facilities. They could probably run at $\lambda/\Delta\lambda \sim 10^3$, but, in view of possible small sample sizes, small focal spots will prove useful, as will high flux. A large horizontal spread, $>$ 50 mrad (200 mrad has been used at LURE) should be collected and focused to keep the flux high on potentially small samples. Fluxes approaching those from U_A could probably be obtained in this way from bending magnets, especially in the spectral range below 20 eV.

One can imagine experiments with these instruments in the following areas: spectrophotometric, including matrix-isolation spectroscopy; luminescence and time-resolved experiments on wide band-gap materials, radiation damage studies, and photoconductivity in short life-time materials such as amorphous materials, and glasses. Work carried out on these instruments might be primarily programmatic research at NCAM in which the use of photons is not the primary experimental tool. These beam lines should be developed later than the others, and be tailored to the development of the NCAM research program. Some of this work could, in fact, be carried out at other sources of synchrotron radiation but Bay-Area users may be numerous enough to justify these lines.

We have recommended more VUV-soft x-ray monochromators than described in the provisional beam line layout in the NCAM description. The two photoemission monochromators could be accommodated as principal instruments on U_A and W_E. The "photochemistry" monochromators could be the secondary instruments on U_A, receiving deflected radiation. There is, however, a better arrangement for the photoemission monochromators. An additional undulator with characteristics between those of U_A and U_B should be built. It would span the 10 or 15 eV to 1 or 1.2 keV region and would serve one wide-range monochromator directly. A second monochromator, with limited energy range, would be served by a reflection, or be placed on W_E. This choice would allow putting one photochemistry monochromator directly on U_A and the other on U_A with a deflecting mirror. The additional funds for the new undulator could be made available by cancelling, or delaying, the construction of the superconducting wiggler. This wiggler emphasizes a spectral region perhaps better dealt with at SSRL. (There are probably reasons for keeping the superconducting wiggler, but we feel an additional undulator, as suggested above, is more in keeping with the expressed capability of the ALS.)

Summary of Monochromator Requirements

Two (or possibly three) high resolution ($\lambda/\Delta\lambda \sim 10^4$) monochromators covering a wide spectral region (10 eV to 1–1.2 keV) with high flux, should be placed directly on a new undulator, $U_{A/B}$, and or W_E. These monochromators will enable desorption studies and photoemission studies of many types.

Two high resolution ($\lambda/\Delta\lambda \sim 10^4$), high-flux monochromators for the 6–30 eV region, should be installed on U_A, one after a reflection, the other directly or also after a reflection, depending on whether the undulator, $U_{A/B}$, suggested above is installed in the ring.

Up to three general-purpose 6 to 30 or 50 eV monochromators of lower resolution ($\lambda/\Delta\lambda \sim 10^3$) should be placed on beam lines originating at bending magnets, but after the development of the insertion-device beam lines.

Time-Structure Considerations

The time structure of synchrotron radiation has made possible a wide variety of experimental techniques that have had important applications in science. These techniques can be categorized as (1) stimulus-response experiments, which utilize a short pulse for stimulus followed by an observation period for response, or (2) steady-state experiments, in which the time dependence of the experimental system induces a change of a steady-state signal. Examples of the former category are fluorescence decay measurements or time-of-flight spectroscopies. In the latter category are phase-shift measurements.

These two experimental categories are facilitated and optimized by different time structures. For the former case, the ideal would be periodic delta-function stimulation pulses with a variable interpulse period, depending on the type of system response encountered. In fluorescence decay experiments, for example, atomic, molecular, or solid matter may emit fluorescence or luminescence over an extremely wide range of decay times — from picoseconds to minutes or longer. Synchrotron radiation experiments offer wonderful opportunities for the study of decay times in the microsecond to nanosecond range, and with narrower pulses down to the picosecond range. Because important scientific questions may hinge on whether or not a fast decay (~10–1000 ps) occurs before one or more slower decays, it is important to make the shortest possible pulses available. Likewise, it is important to be able to distinguish single and multiple exponential decays, non-exponential decays and decays representing two closely-spaced lifetimes. These demanding experiments require the widest available dynamic range. Techniques for wobbling the electron beam by using, say, matched bump and kicker magnets for artificially lengthening the present maximum 0.5 μsec interpulse period can be employed to advantage. Note that there is no "down-stream" technique available for uniquely deconvolving a too-frequent excitation in these complex situations.

Time-of-flight techniques are generally less demanding of the source time structure. Electron time-of-flight spectroscopy is limited by the excitation pulse width and the speed of the detection electronics. Ion time-of-flight may require longer interpulse periods for heavy ions. In both cases the availability of variable accelerating or retarding electric fields is a considerable aid to the experimenter.

One valuable technique of surface science that depends on time-of-flight detection of ions photoemitted by synchrotron radiation is photon-stimulated ion desorption (PSID). Here increased photon flux would enable the full realization of the technique. Three goals, listed in order of their increasing need for photons, are (1) time-of-flight mass identification of desorbed ionic species, (2) spectral identification of desorption thresholds to identify surface bonding partners, and (3) PSID EXAFS spectra above the thresholds to identify the *local* desorption-site geometry, whether imperfect or not. With a photon flux of the order of 10^{10} photons/sec per square millimeter, and an effective cross-section of 10^{-8} ions/photon (we have observed 10^{-6} to 10^{-9}), one can now identify 10^{-3} monolayers of adsorbate, observe thresholds for 10^{-2} monolayers, and barely obtain EXAFS data for a full coverage. An increase of 10^3 in flux onto 1 mm^2 of surface would make studies of imperfections and rare surface sites an exciting possibility. Note also the need for single-bunch time structure to obtain both mass resolution and sensitivity to rarely-desorbed species in the presence of large peaks.

In fluorescence-decay experiments, RF buckets adjacent to the "full" bucket need to be empty of electrons on the level of 10^{-4} the charge of the "full" bucket. This is *not* easy to do and the engineering needs to be done carefully on the injection linac and both rings.

For steady-state experiments, the ideal time structure is a much higher duty cycle with possibly a variable pulse *shape*. In these experiments, the phase shift of one or more harmonics of the synchrotron radiation excitation is recorded as the experimenter varies something in the system. Hence one is interested in directing as much power as possible into the harmonics to be detected, by choosing the pulse shape, and *maximizing* the duty cycle. The key noise factor lies in pulse shape instabilities, which must be carefully considered in the design of such phase-shift or steady-state time-resolved experiments. If the pulse shape is stable enough to allow high harmonics to be used, such experiments may open new scientific areas. Subpicosecond phenomena may be studied in the linear (weak) excitation regime, complementing picosecond laser studies which utilize the strong excitation regime. It may not be possible to design a synchrotron-radiation source which *always* has a stable pulse shape, but it may be possible to *monitor* the pulse-shape stability, or at least to tabulate machine conditions under which the pulse shape may be assumed to be stable.

For ultrashort timing measurements (nanosecond and below), bunch-profile (longitudinal) stability is critical. The ring operators should have clear indications of bunch stability. It would be desirable for the users to have direct indications for their own analysis. A complete catalog of bunch longitudinal operating conditions, e.g., bunch-length stability limits, as a function of current and energy should be prepared and disseminated for user planning.

High-stability ($\approx$10 ps) triggers derived from the beam should be available to the experimenters. Dedicated pick-up electrodes with broadband feedthroughs for users should be designed into the vacuum chamber. Space should be available for, e.g., 6 inch Heliax cable leading from these electrodes to user electronics. This is especially critical for the new phase-shift timing technique. Fast diodes near the user can also be used for timing purposes. Fiber optics may prove useful for transmitting timing information.

It might also be noted that light pulses passing a grating may be broadened or otherwise changed in shape. Such effects may be significant, especially with the small pulse width of the ALS. A small ruling width reduces this effect. If 20 mm of a 1200 l/mm ruling is illuminated with $\lambda \sim 1000$ Å, an additional pulse width of ~10 psec will occur. The use of two gratings can cancel this effectively. In phase *shift* experiments, of course, this effect only changes the power directed into the desired harmonic (and therefore the signal-to-noise ratio), but not the basic accuracy of the experiments.

Related to the time structure of synchrotron radiation is the possibility of combining laser and synchrotron radiations. Because these are complementary in so many ways, such as coherence, ease of tuning, wavelength ranges covered, strength of excitation, etc., it seems safe to predict a growing utilization of both types of radiation in a single experiment. Two-photon absorption and photoemission were early examples, but many other experiments and techniques may be devised in the future. It seems reasonable to suggest that the ALS could serve the goals of NCAM better if it were equipped with lasers. For example, an eximer- or nitrogen-pumped dye laser (already synchronized to the synchrotron radiation) could be made available to users in a "portable" mode for use at any beam line. The user would need only to vary a delay time slightly to account for beam-line length, variations in the experimental chamber, or the position of the beam line in the orbit. Other lasers may be a better choice for certain experiments, but the tuneability of the dye laser and the power and efficiency of the eximer or nitrogen lasers make this combination attractive. Certainly adequate space and power for lasers should be available on the floor of the ALS.

Attention must be paid to the electromagnetic interference from the ring, especially from feed throughs: these should be shielded. An EM interference survey should be carried out in the experimental area as soon as possible. The use of pulsed lasers will exacerbate the interference problem. Isolated power lines and electromagnetic shielding for lasers must be provided.

In summary, time-resolved spectroscopy using synchrotron radiation is a valuable scientific tool of broad applicability. Care, thought and budgetary commitment should be applied to optimize the ALS facilities for this technique.

3 Report from the Working Group on Soft X-Ray Beam Lines*

Introduction

This report summarizes the recommendations regarding the insertion devices, beam-line configurations and monochromators to be installed on the Advanced Light Source (ALS) for use in the soft x-ray range. Based on projected scientific programs using high-brilliance, soft-x-ray undulator and wiggler radiation we propose schemes for beam lines that should meet the spectral requirements. Because of the unique difficulties in obtaining high-intensity monochromatic radiation in the spectral region above the carbon K edge (~280 eV) and below the beryllium window cut-off (~3000 eV), we specifically address this energy range.

The so-defined soft-x-ray region is best covered using an undulator as the source and we specify what undulators are best suited. We also discuss the utilization of wiggler and bending magnet radiation and point out that beam lines originating from such sources are best utilized in "bread-and-butter" type experiments in conjunction with materials and surface science problems in NCAM. We address the issue of time-sharing between different end-of-line stations utilizing the same source and conclude that undulator beam lines in the soft x-ray range are best and most economically utilized by using a single monochromator with the possibility of directing the monochromatic radiation into different sample chambers downstream of the monochromator. New schemes of accomplishing this are suggested. The soft x-ray region cannot be covered by a single type of monochromator, but rather reflection grating ($\lesssim$1000 eV) and crystal monochromators ($\gtrsim$1000 eV) need to be utilized. We discuss problems associated with different monochromator types and comment on the possible use of transmission gratings. Finally we identify projects which could lead to significant advances in soft x-ray science.

Present and Future Experiments

Since ALS will start operating at the end of this decade it is difficult to describe particular experiments that will be interesting and important at this time. We therefore will discuss classes of experiments that might be desirable or made possible by the new ALS.

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*Joachim Stöhr (Exxon), Group Leader, J. Barton (LBL), W. Eberhardt (Exxon), F. Himpsel (IBM), M. Howells (NSLS), S. Kevan (Bell Labs), K.J. Kim (LBL).

In more detail we foresee the following categories of experiments:

Photoemission experiments certainly will be important, especially with increased energy and/or momentum resolution or spatial resolution at the sample. High energy-resolution ($\lesssim$50 meV) core-level spectroscopy, especially from minority species on surfaces like adsorbates on steps or defects as well as gas-phase samples requires a high photon flux. An interesting application for photoelectron spectroscopy might be in the construction of a *photoelectron microscope*, where the photoelectrons from the sample get imaged and energy analyzed through a spectrometer conserving the spatial information from the illuminated sample area and projecting its energy-resolved image onto a video screen. Alternately, by using a zone plate or a multi-layer normal-incidence optical element one should be able to construct a *photoelectron or fluorescence microprobe*. Both devices could have a resolution of about 500Å. Spin-polarized photoemission includes another dimension of information and therefore is very hungry for photons. The same is true for *time-resolved photoemission* where one tries to monitor chemical or otherwise-induced changes in the sample in a real-time experiment.

Present SEXAFS measurements are often limited by poor signal-to-noise contrast resulting from insufficient photon flux. Increased flux would not only improve the reliability and accuracy of electron-yield SEXAFS studies, but also allow *fluorescence SEXAFS*, even on low-yield elements like C, N and O. Fluorescence SEXAFS enhances the signal-to-background ratio over standard total or partial electron-yield SEXAFS, and with higher photon flux will ultimately be the superior detection mode. By the same token *x-ray fluorescence* experiments on dilute systems will be possible.

Photon-stimulated desorption also can profit from a much higher photon flux than that available from existing synchrotron-radiation sources. In addition, electron-ion coincidence experiments become possible.

Any kind of *time-resolved spectroscopy* will benefit vastly from the additional flux out of an undulator. Besides the time-resolved photoemission studies mentioned above, two other classes of experiments bear listing. *Electron-ion coincidence* studies elucidate the various channels in the fragmentation of chemisorbed or gas-phase molecules following soft x-ray excitation. *Electron-electron coincidence* studies probe the coherence between directly excited core electrons and Auger electrons generated in the decay of the same core hole. Using time of flight (TOF) detectors these experiments will also make use of the special synchrotron time structure, at least when only a few bunches ($\leq$4) are circulating in the ring. TOF techniques will enhance the detection efficiency by about two orders of magnitude. The construction of a *wobbler*, lifting only a specially selected bunch into the acceptance window of the monochromator optics, would allow time of flight experiments at even higher bunch occupancies. We have summarized the spectral requirements of these experiments in Table 3-1.

Table 3-1
Experiment Requirements

Experiment	Flux (photons/sec)	Spot Size (mm)	ΔE (meV)	Scan Mode	Maximum Harmonic Content (%)	Timing	
						Puls. Width (psec)	Rep. Rate (nec)
XPS GAS	10^{15}	0.1* 1.0	<30	Discont.	10.0	100*	250*
XPS SOLID	10^{12}	<0.5	100	Discont.	10.0	(100)*	(250*)
ARPEFS	10^{13}	<0.5	100	Cont.	1.0		
SEXAFS	10^{13}	1.0	2000	Cont.	0.1		
NEXAFS	10^{12}	1.0	100	Cont.	1.0		
PSID	10^{15}	1.0	100	Cont.	0.1	100*	500*
FLUORESC.	10^{15}					35	2500†
TIME RESOL.	$>10^{15}$					35**	1

* For Time-of-flight experiments.
† Wobbler required.
** Stable pulse shape required.

Insertion Devices and Beam Lines

Of the previously suggested insertion devices, the three hybrid undulators U_B, U_C, and U_D were designed specifically to service the soft x-ray region. None of these however, will span the range between the "valence spectroscopy" ($h\nu \lesssim 50$ eV) and the "core level" ($h\nu > 200$ eV) regions. In addition, it appears impractical or too expensive to install more than one monochromator on a particular undulator line as would probably be required to utilize the full range of undulators U_B and U_C. We suggest that these deficiencies be alleviated by changing the spectral output of both undulators, U_B and U_C from 75—3000 eV to 20—1500 eV. Calculations show that this is possible without sacrifice in photon flux using the parameters listed in Table 3-2. This range can be entirely serviced using reflection grating monochromators and will allow, for instance, sequential studies of electronic and geometric structures on a single sample preparation. We find the energy range proposed for U_D to be a good complement to these values for U_B and U_C.

Table 3-2
Summary of Currently Planned ALS Insertion Devices (1.3 GeV)
Showing Suggested Revised Specifications For U_B/U_C

NAME	INSERTION DEVICE Type	PEAK FIELD (T)	PERIOD (cm)	NO. OF PERIODS	LENGTH (m)	E (eV)
U_A	Permanent Magnet Undulator	0.29	16.7	30	5.0	8 — 200
U_B/U_C	Hybrid Undulator	0.46	6.25	80	5.0	20 — 1500
U_D	Hybrid Undulator	0.57	3.5	142	5.0	200 — 5000 (up to 10000 at 1.9 GeV)
W_E	Hybrid Wiggler	1.60	10.0	25	2.5	0.1 — 10000
W_F	Superconducting Wiggler	5.0	14.0	14	2.0	1 — 20000 (up to 40000 at 1.9 GeV)

The best use of the ALS facility will result from maximum utilization of the undulator beam lines. Unfortunately, the extreme collimation and tunable spectral character of the emitted radiation impedes simultaneous operation of several experiments. In addition, the expense of soft x-ray monochromators and the desirability of utilizing the smallest number of optical deflections indicate that the most reasonable beam-line layout in this regime consists of *one monochromator per undulator*. The exit beam from the monochromator could then be switched from one experimental station to the next. A novel technique for accomplishing this overcomes the necessity of a reflection and is indicated in Figure 3-1. Two or more experimental stations are mounted on a rotating pie-shaped platform centered on a bellows. Adequate space between experimental stations should be possible, and beam time could be shared between the experiments by a simple rotation of the platform. We suggest that such a structure be given serious consideration for all the soft x-ray undulator beam lines.

It is not our intention to make specific recommendations concerning the type of monochromator to be installed on the various soft x-ray beam lines. Our general comments are as follows:

1. Undulator U_B and U_C, as mentioned previously, should service extended-range, reflection-grating monochromators. The next 1—2 years will provide ample testing of the various designs in existence. We recommend, however, that the two monochromators be of different designs; rarely can one design outperform all others in all characteristics.

2. Undulator U_D should service an ultra-high-vacuum crystal monochromator. The design should be general enough to allow use of standard and state-of-the-art (e.g., multilayer) crystals.

3. We recommend installation of a vacuum crystal monochromator on one of the wiggler lines, W_E or W_F. This line will service experiments which are less photon-intensive than those performed on U_D, and will ease pressure for time on that line.

4. Finally, we envision several soft x-ray beam lines installed on bending magnets to service the more time-intensive experiments (routine photoemission, SEXAFS, etc.)

5. These time-intensive experiments would be well serviced by facility-supplied experimental chambers and sample-introduction systems.

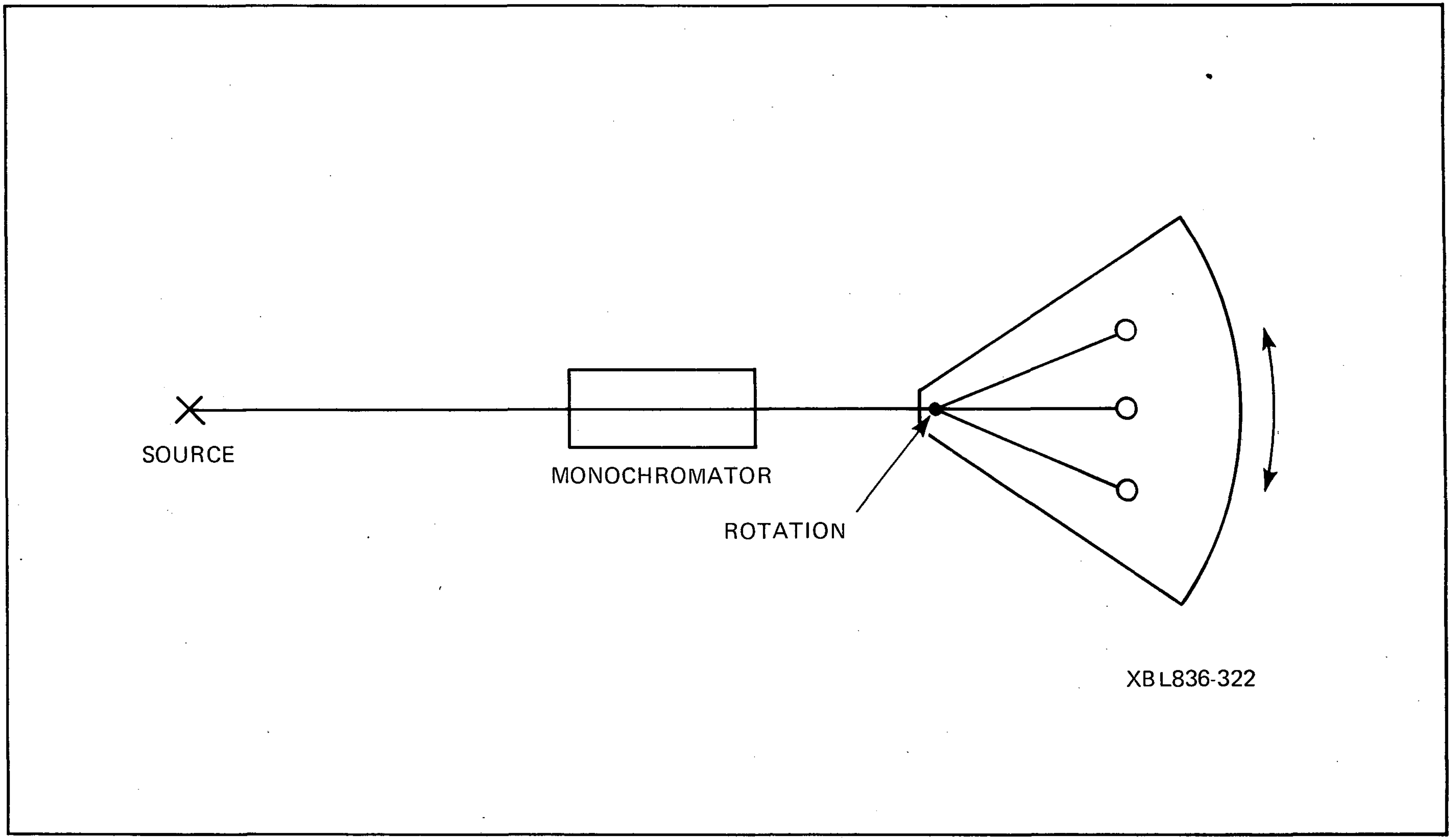

Figure 3–1. Possible rotating platform to permit selection of one of several experimental stations on an undulator beam line.

6. It appears that a significant advance in obtaining soft x-ray radiation could be made if an undulator could be designed with a tuneable first harmonic of ~1% FWHM in the 250—1000 eV spectral range. This device should have a small K value to suppress higher harmonics and could thus be used without a monochromator. Unfortunately the scan range for a transverse undulator is limited to ~50 eV, but it appears that a helical undulator may be adaptable Figure 3-1 tuning both the magnetic field and the period. This possibility should be explored further.

Monochromators

Three different types of monochromators in current use are appropriate in the soft x-ray range. Reflection-grating monochromators can obtain high energy resolution in the low energy part of the soft x-ray range. Zone-plate monochromators give very smooth spectral output in this same range. Above 1500 eV, the best choice is probably a crystal monochromator. In this section we discuss the features and limitations of each of these types of monochromators.

Reflection-Grating Monochromators

For a soft x-ray undulator (20 — 1500 eV), curved and plane-grating designs are the most natural choices. These monochromators are particularly suited to undulator sources that give a narrow beam of nearly parallel light. Suitable plane-grating designs can be made to accept the entire ALS beam. The possibilities for using curved gratings are presently limited to two cases: Rowland-circle monochromators with large radii of curvature, and toroidal-grating monochromators (TGMs).

Rowland-circle monochromators for the ALS will require radii of curvature much larger than presently utilized values. This limitation arises from the very narrow slit widths that must otherwise be manufactured, aligned, and filled with light. Radii greater than about 20 — 30 m would be needed.

Toroidal-grating monochromators typically have major radii in the above range. The University of Pennsylvania design for a bending-magnet TGM beam line shows a significant improvement in resolution if only a small width of the grating is illuminated. With an undulator source, in fact only a small area would be illuminated. Thus a TGM might be a good choice for the ALS. Therefore the performance of the University of Pennsylvania instrument should be watched carefully.

We do not wish to suggest a choice for a plane-grating monochromator at present because the facts are not in on a number of instruments, and we wish to hold open the option that the Pennsylvania TGM might be a good selection. However, the following consideration should guide the choice of a plane-grating instrument. The basic standards for plane-grating design were set in 1968—72 by Kunz and co-workers, and their monochromator is an excellent model, apart from its non-UHV character. The various other plane-grating monochromators that have been made since then should be judged according to whether they achieve the performance of an optimized Kunz instrument and whether they can accept the whole beam of the ALS undulator. So far all are resolution-limited by the angular subtense of the source. Finally we believe that it should be possible to buy either type of instrument from industry, and this course is recommended in light of the special experience possessed by engineers who build monochromators for a living. We expect that cost will be a major factor in selecting designs.

Zone Plate Monochromators

A zone-plate monochromator[*] offers prospects for obtaining a smooth spectral output. This feature is essential for SEXAFS and photoelectron diffraction work at and above the carbon K edge where carbon contamination of the elements modifies the spectrum of the output beam. The monochromator (see Figure 3-2) contains as the only optical element a Fresnel zone plate, i.e., a free-standing transmission grating (period ≥ 2000 Å) to focus the synchrotron radiation onto a fixed exit slit. The wavelength is scanned by translating the zone plate. The characteristic design values for a prototype are given in Table 3-3.

Table 3-3
Approximate Parameters for a Zone-Plate Monochromator

Tuning Range:	4:1 per zone plate; four zone plates to cover 10–1000 eV range)
Acceptance:	1×1 mrad^2
Resolving Power:	$\lambda/\delta\lambda = 1000$ at 0.1 mm beam height 10 m from source
Efficiency:	$\simeq$10%

The principal problem anticipated with this monochromator at a high-brilliance light source is the heat load. Using the input power of 0.5 W/mrad^2 at the NSLS UV ring a temperature rise of ≤ 50°C is estimated for a zone-plate structure where a support grid conducts heat away. This should not distort the grating significantly. Heat loads from undulators will be difficult to handle at the projected power level of about 20W for the central image alone.

Crystal Monochromators

The most suitable scheme for a crystal monochromator in the soft x-ray region is shown in Figure 3-3a. The radiation from an undulator is filtered and focused by a double mirror arrangement. The variable grazing incidence angle $0.5° < \alpha < 5°$ both eliminates higher harmonics and reduces the power. One of the mirror surfaces may be curved in order to focus the source onto the sample and thus reduce the spot size. The dual mirror assembly is arranged so that for different incidence angles, α, the exit beam does not move significantly. This is achieved most easily if the mirrors are positioned close to the monochromator.

The ultrahigh-vacuum (UHV) compatible monochromator is of a double-crystal design to keep reflectivity losses at a minimum while satisfying the requirement of a spatially fixed exit beam. Several schemes for rotating both crystals and translating one crystal in UHV have been developed, and it is believed that reliable monochromator schemes exist. The main problem is the unavailability of suitable crystals in the energy range below the silicon K edge (~1830 eV). Table 3-4 summarizes suitable crystals for the soft x-ray region.

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[*] E. Spiller in "Workshop on X-ray Instrumentation for Synchrotron Radiation Research," ed. by H. Winick and G. Brown, SSRL Report No. 78/04 (1978), p. VI-44.

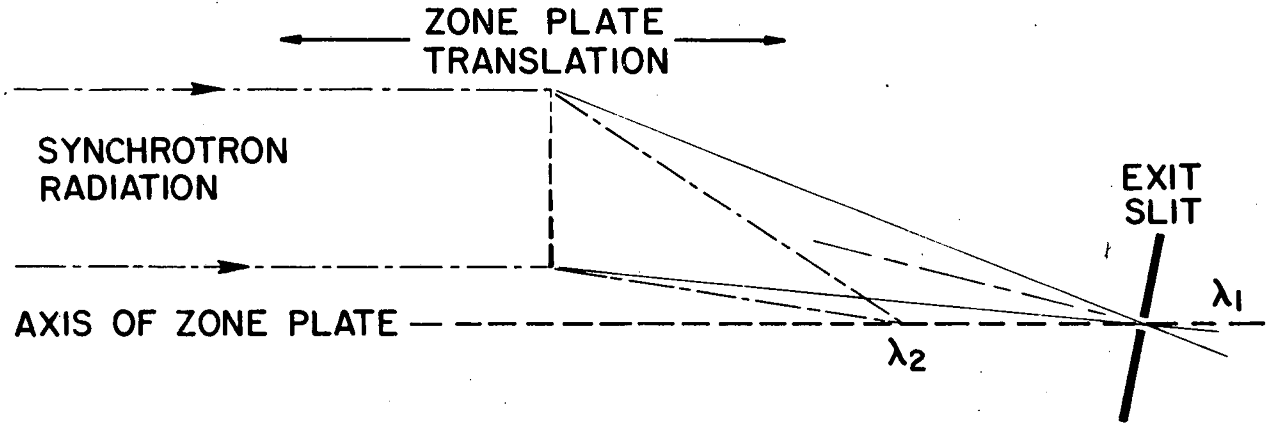

Figure 3–2. In a zone-plate monochromator the wavelength is scanned by translating the zone plate.

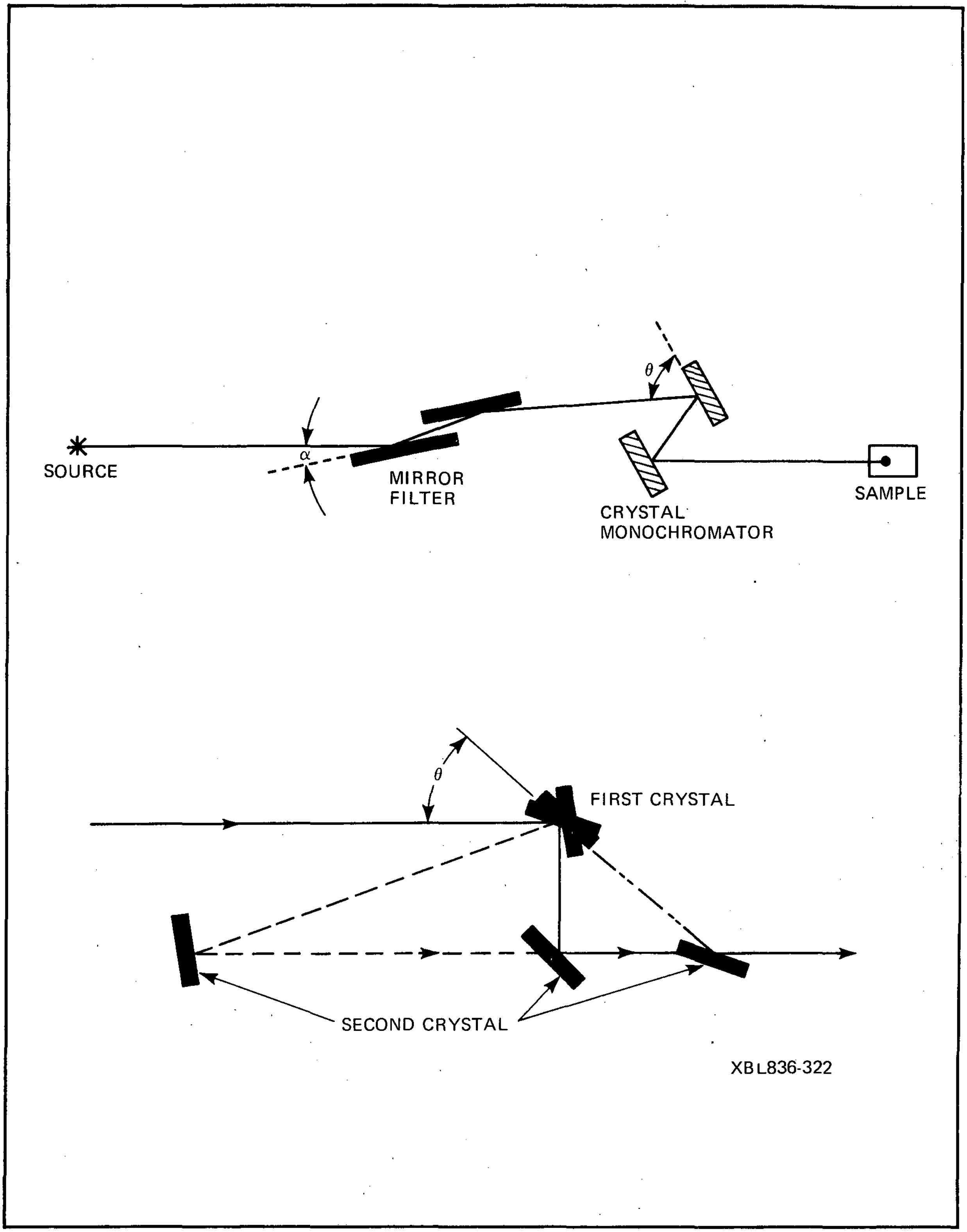

Figure 3–3. Scheme for a double-crystal monochromator beam line. (a) Use of a mirror filler to eliminate higher order harmonics of the selected energy. (b) Double-crystal configuration that maintains a spatially fixed exit beam. Energy is scanned by rotating the first crystal and simultaneously rotating and translating the second crystal. Three example configurations are shown.

Table 3-4
Monochromator Crystals in the Soft X-Ray Region
for Synchrotron Radiation Use

Crystal	2d Spacing (Å)	Suitable Energy Range (eV)	Double-Crystal (1,-1) Rocking Curves, FWHM (eV) (Exp.)	(Theor.)
Si(111)	6.284	2000–5000	0.3–0.7	0.3–0.7
Ge(111)	6.532	1930–5000	0.6–2.0	0.6–1.6
InSb(111)	7.4806	1690–5000	1.5–6	-
α-Quartz ($10\bar{1}0$)	8.512	1480–1860	0.2–3[b]	0.13–0.15
YB_{66}(400)[a]	11.76	1050–2000	-	0.5–0.7
Beryl($10\bar{1}0$)	15.96	800–1550	0.4–1.0	0.4–0.7
β-Alumina(200)[a]	22.53	560–1550	5–7	0.6–2.0
Synthetic Multilayers[a]	~20–150	~100–1000	~5–50	1–20

[a] Not yet available

[b] Highly subject to radiation damage.

Beryl ($10\bar{1}0$) can be used from 800 eV to the aluminum K edge (1560 eV) and Quartz ($10\bar{1}0$) from 1550 eV to the silicon K edge (1830 eV). For both crystals the spectral range is limited towards higher energy by absorption in the crystals (i.e. Al and Si as constituents). Quartz is also susceptible to radiation damage and deteriorates within hours of beam exposure even with presently available bending magnet radiation ≤4 keV. In the future, better suited crystals need to be developed and it appears that this might be done ideally within the Advanced Materials Synthesis Laboratory of NCAM.

One possible solution to overcome the scarcity of suitable natural crystals is the production of synthetic multilayer structures. Such structures have been tested for their perfection using x-ray diffraction techniques and found to be suitable as monochromator crystals.

Table 3-5 shows calculations for two possible multilayers which could be used for the spectral region 250–850 eV and would thus allow experiments near the carbon, nitrogen, and oxygen K edges. A 300-layer Ni-B sandwich in theory yields a reasonable reflectivity (10–20%) and moderate resolution (~4 eV) which would be sufficient for SEXAFS measurements. A 500 layer NiBe-Be multilayer has even more favorable characteristics (<3 eV resolution, 14–40% reflectivity). Table 3-5 indicates the great potential of such devices as soft x-ray monochromator crystals.

Table 3-5
Synthetic Multilayers for the 250–850 eV Spectral Range

1. Ni - B $t_{Ni} = 10.18$ Å; $t_B = 15.0$ Å
$N = 300$ Layers

λ(Å)	θ	Δθ	E/ΔE	I/I_0(%)
15.16	17.7	0.076	241 (ΔE = 3.4)	22.4
23.44	28.1	0.25	122 (ΔE = 4.3)	28.5
33.7	42.6	0.53	99.4 (ΔE = 3.7)	16.5
45.1	64.9	1.5	81.5 (ΔE = 3.4)	10.0

2. NiBe - Be $N = 500$ Layers

λ(Å)	θ	Δθ	E/ΔE	I/I_0(%)
15.16	17.65	0.06	304 (ΔE = 2.7)	40.0
23.44	28.0	39.2	175 (ΔE = 3.0)	39.2
33.7	42.45	0.35	150 (ΔE = 2.5)	22.8
45.1	64.58	0.92	131 (ΔE = 2.1)	13.6

We propose to implement a UHV double crystal monochromator on the undulator beam line U_D with a spectral range 200–5000 eV. We note that such an undulator source is ideal for the use of multilayer monochromator crystals, since it does not emit visible and UV radiation. Thus specular reflection of low energy radiation by the multilayers (which act as mirrors for low hν) is avoided and the exit beam does not contain any low-energy photon contamination which would be a severe problem for a wiggler or a bending magnet source.

Special Requirements for Timing

Many new experiments will be able to use the time structure of the ALS to gain additional improvements in detectability. With 35 psec pulses every 500 nsec, efficient time-of-flight (TOF) techniques allow measurements of electrons and ions to be ~100 times more sensitive. To capture the full advantages of the TOF techniques will require a commitment to operate the ALS in a few bunch mode, and also require careful consideration of the needed time structure in the design of the accelerator.

As indicated in Table 3-1 time-of-flight measurements with the pulsed structure of the ALS require 1 or 2 full buckets per machine cycle (250–500 nsec pulse period). Operation of the machine in a 1 or 2 bunch mode reduces the total flux for non-timing experiments. Thus any development which improves beam conditions while allowing long pulse periods will increase the productivity of the ring. Two specific suggestions are sacrificing pulse width (up to 200 ps) for ring current and constructing a bucket selecting device, such as a wobbler. *Since 35 ps pulses are not crucial to TOF techniques, trading pulse width for bucket current will increase the usefulness of 1- or 2-bucket operation.* We recommend that this mode should be frequently available. The bucket-selecting "wobbler" should be included in the initial ring design if side-tracking single buckets is feasible.

In selecting monochromators for use with 35-picosecond-pulsed synchrotron light, optical path-length differences must be considered. Since a 1 cm path-length difference will lead to a 33-psec timing spread for light, compensating optics must be used to preserve this ultra-short pulse length. Ultranarrow pulses will be used primarily for fluorescence measurements using 10–30 eV photons suggesting that one of the low energy lines should seek to provide 35 psec pulse structure. Higher energy lines should, however, keep optical path differences below 4 cm to allow efficient use of time-of-flight techniques.

Of related importance for monochromator design is the output beam size. All time-of-flight techniques require small beam size to give good resolution. Thus tightly focused beams (~100 μm) will greatly improve TOF measurements.

4 Report of the Working Group on Hard X-Rays*

Introduction

Research in the hard x-ray portion of the electromagnetic spectrum has undergone a renaissance in recent years, owing to the availability of intense, highly collimated beams of radiation from electron storage rings. The continuous improvement in the electron-beam properties and in the magnetic sources utilized for generating the radiation have resulted in roughly an order of magnitude improvement every two years in spectral brilliance available for routine utilization since the sources became generally available in the early 1970's. This improvement has derived from the close cooperation between the physicists, who design the storage rings, and the scientists, who ultimately use them as research tools. In particular, the Stanford SPEAR ring with its nominal 3-GeV electron energy, has served the community well as a synchrotron radiation source in the hard x-ray portion of the spectrum, as well as in the VUV and and soft x-ray portions of the spectrum. Nevertheless, as we shall see, it has not reached its full potential as a radiation source. Moreover, its bigger cousin, PEP, stands as a potentially phenomenal source of hard x-rays, and will be perhaps the means of realizing the dream of very high brightness electron beams mated to x-ray undulators. Finally, for the ALS storage ring, it will be possible to generate high-intensity x-ray beams through the utilization of superconducting wigglers.

In what follows, we shall briefly outline the scientific possibilities that can be realized in the hard x-ray portion of the spectrum with resources potentially available through the NCAM program. We will conclude with a series of recommendations resulting from the deliberations of the hard x-ray working group, integrating the ideas presented in the plenary session.

Scientific Possibilities

Important new scientific initiatives will be made possible by developing an x-ray undulator on PEP. Among these initiatives are high energy-resolution x-ray scattering, protein crystallography at high x-ray energies, resonant nuclear diffraction, Compton scattering at high resolution, and high-energy microprobes. If history is any guide, the availability of x-ray beams orders of magnitude brighter than existing sources will open fields of study not yet imagined. Furthermore, the PEP undulator beam will provide an opportunity to study the technical problems

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associated with high-energy undulator beams, well in advance of dedicated x-ray undulator-based storage rings.

Intense, highly monochromatic hard x-ray beams will make possible new classes of experiments in nuclear scattering. With an intense source, Mössbauer experiments will be able to probe interesting temporal changes that occur in the nucleus, such as time-varying chemical valence states. It will be possible to perform a new class of Mössbauer experiments to study atoms in deliberately excited chemical or electronic states. The "soft" end of the phonon spectra (say 10^{-6} to 10^{-4} eV) may become observable for the first time by looking at phonon-broadened nuclear lines. Completely new prospects for x-ray interferometry may open up, since the beam may have a coherence length greater than ten meters. Finally, the study of novel, intensity-dependent phenomena associated with nuclear lasers may become possible with the photon beam from the proposed undulator on PEP. This radiation should stimulate thousands of simultaneous nuclear excitations in a sample. Superradiant decay of these nuclei proceeds with uncharacteristically short lifetimes.

With an undulator on the 15-GeV storage ring PEP the dreams of measuring energy transfers with 1-meV resolution may become a reality. This possibility would allow studies of the statics and dynamics of small samples and surfaces, and, because of the photon energies involved ($\sim$10 keV), excitations with energies of $\sim$1 meV can be measured easily. Very likely, the simplest way to achieve photon beams with the required energy resolution is to use a backscattering geometry. Designs exist for a suitable monochromator, which would, however, be technologically challenging to construct.

An x-ray microprobe would be well suited for the upgraded SSRL. It should achieve a 3 μm spot, over an energy range of 2–17 keV, with $E/\Delta E \sim 50$. The energy range and resolution were chosen to span elements 10 $\sim$ 90 in the periodic chart with either the K or L_{III} edges. The microprobe would observe the fluorescent radiation produced from the filling of core holes created by the incident photon beam. By scanning the sample in a suitable raster pattern, it would be possible to produce maps of the elemental distributions. The advantages of an x-ray microprobe are the ability to do quantitative analysis at the ppm level with spatial resolutions perhaps as good as 0.5 μm.

An x-ray-scattering beam line on the existing SPEAR machine, if configured as a single end-station beam line illuminated by a multipole wiggler, will provide a roughly threefold increase in brightness over the existing scattering beam line. This will provide a qualitative improvement in the scattering research program, by facilitating studies of monolayers on single crystal substrates, low Z adsorbates, and 2-dimensional liquid correlation functions.

Small-angle x-ray scattering at SSRL is currently limited by two major considerations: beam stability and source emittance, both of which have the effect of smearing the instrument focus and directly limiting the minimum values of scattering angle obtainable. Currently, approximately 90% of the flux must be discarded in order to achieve acceptable focal conditions. Emittance reduction would simplify the required x-ray optics, make the full flux available, and simultaneously result in a reduced image size. With a stable beam a small-angle x-ray scattering spectrum could be acquired in 100 msec or less at scattering vectors down to 1.5×10^{-3} Å^{-1}. Thus, irreversible kinetic processes involving objects up to 500 Å in size could be studied where total process times were of the order of a few seconds. Plentiful examples of such processes occur in polymers, glasses, and biological materials.

A superconducting wiggler on the ALS will provide significantly greater brightness in the 5 to 40 keV range than is presently possible on SPEAR. This follows from the fact that the wiggler brightness at ω_c scales as $\gamma^2 NI/\sigma_x\sigma_y$ where N is the number of periods, I is the current, and σ_x and σ_y are the electron-beam transverse dimensions. The γ^2 advantage at SPEAR is roughly compensated by the ALS projected current, but the ALS beam size is two orders of magnitude smaller than the present SPEAR beam size. This increased brightness at x-ray wavelengths results, for example, in a direct improvement in the resolving power achievable with an x-ray microprobe, and with other imaging techniques.

For many routine studies and especially for experimental applications of synchrotron radiation to clinical medicine, currently available intensities, energy ranges, and emittances are perfectly adequate. What limits these studies is the availability of beam time, especially during the summer. Operation of SSRL throughout the year and turn-on of the ALS very likely would attract more clinical users while simultaneously increasing the total amount of research that can be done.

Proposed Improvements to SPEAR

Part of the objective of the SSRL upgrade is to improve the capability and effectiveness of SPEAR as a synchrotron radiation source. Here we discuss only improvements to the storage ring itself.

Three planned SPEAR machine improvements—the new linac gun, improved photon-beam steering and electron-beam orbit control, and a new SPEAR operations configuration—were presented to the workshop.

A new gun is planned for the SLAC linac for nuclear physics studies which require high-intensity electron beams below about 4 GeV. SSRL will contribute to this project to make the gun capable of producing a short pulse suitable for SPEAR injection. Because the new gun injects into the linac near the high-energy end, only the last 1/5 of the linac is used for SPEAR injection. This opens the possibility for SSRL operation during the summer months when SLAC is normally not in operation.

It is planned to employ many SPEAR orbit correctors to provide very flexible control over the vertical electron-beam orbit. Desirable consequences of this improvement include:

1) More independent steering of each beam line.

2) Higher frequency response with attendant reductions in "beam bounce" and improvements in beam stability. Noise and "beam bounce" presently are limiting factors on some experiments, such as diffraction experiments on protein crystals and the angiography study.

3) Improved reproducibility of SPEAR orbit.

4) Higher quality data for SSRL users (better signal/noise ratios).

A new operations configuration for the SPEAR magnets will be developed with stronger focusing, thereby providing a reduced emittance and having a smaller required aperture for the electron beam. Reduced emittance results in higher brightness for all source points and improved performance of undulators (sharper peaks). Specifically more photons would get through most VUV monochromator systems (particularly the grasshoppers) and some x-ray systems (particularly the small-angle scattering line, I-4). However, reduced emittance may magnify the problems associated with beam instabilities. The reduced required aperture permits the use of smaller-gap insertion magnets with increased field and/or shorter period. The precise configuration will be determined by further analysis. Recent work by Roy Blumberg (NSLS visitor) and Rubin Liu (Hefei visitor) shows promise for a new, simpler approach to achieving the desired configuration. Very likely the new configuration will achieve a four-fold reduction in emittance, and a 25% reduction in the required aperture.

Recommendations of the Study Group

The x-ray working group has formulated a set of recommendations based upon the consideration of the scientific opportunities listed above. These recommendations are as follows:

1) SSRL should proceed to implement a fully instrumented undulator beam line on PEP as soon as possible.

2) SSRL should also implement a scattering beam line on a SPEAR straight section. If the only available straight section is presently occupied by a kicker magnet, then SSRL should take whatever steps are necessary to develop the technology of in-vacuum wigglers and undulators.

3) SSRL should undertake a significant effort to improve the low- and high-frequency stability of the SPEAR electron beam.

4) SSRL should take appropriate steps to insure that adequate set-up space and facilities are maintained as new beam lines progressively take up existing space.

5) SSRL should provide for year-round operation and increase, if possible, the amount of running time dedicated to synchrotron radiation use.

6) The ALS should proceed with installing the proposed superconducting wiggler if resources permit and if there is convincing evidence, either theoretical or experimental, that the device will not seriously compromise the machine performance.

5 Report from the Working Group on High-Brilliance VUV Chemistry*

Photochemistry and Reaction Dynamics

The ALS will provide an unprecedented intensity and tunability in wavelength ranges where currently available tunable lasers do not operate well. Among such spectral regions, the VUV and IR are of particular interest to chemists.

While the availability of the ALS promises to open up new areas of chemical research, it is important to note that the pulse energy of the ALS is much smaller than that of typical lasers. The product of the ALS photon fluence and a typical VUV absorption cross section is too small for excitation of a large fraction of a sample. Except for studies in which either photons or ions are detected, successful experiments with the ALS will require either many molecules in the sample or long integration times. For example, it is clear that the fluence available from the ALS will permit VUV photoreaction of liquids and high pressure gases over time spans of minutes or hours to be carried out easily.

One important advantage of working in the VUV is that the photon energies are often sufficient to induce chemical reactions leading directly to the production of electronically excited states and/or ions. Since such products can be detected with high sensitivity, the ALS output is sufficient to open new horizons in research on the chemistry of highly-excited molecules. While such single-pulse experiments offer considerable promise, current work in photochemistry and reaction dynamics suggests that many experiments will typically require two optical sources, one for preparation of the specific species and states to be studied, the other to probe the dynamics of the ensuing reactions. Such experiments will no doubt take two distinctly different forms. In the first, a laser that can excite a large portion of the sample will be combined with the ALS as a probe of the evolution of the excited states produced. In the second, the ALS itself may be used to generate modest numbers of excited states which may then be observed by ultra-sensitive laser-based detection techniques, e.g., laser-induced fluorescence or multi-photon ionization.

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The potential of the ALS for opening new and important areas of chemical research may be put into perspective by comparing the product of the photon fluence, Φ, in photons/cm^2 and a typical VUV absorption cross-section, σ, in cm^2. For conventional, continuously tunable VUV light sources, $\sigma\Phi$ is roughly 10^{-7}. The ALS offers the opportunity to achieve $\sigma\Phi$ products in the range from 10^{-4} to 10^{-3}. Free-electron lasers could potentially achieve $\sigma\Phi$ products greater than unity. For each of these substantial improvements, entirely new classes of experiments become possible.

Some quantitative examples follow to illustrate potential research directions and the corresponding source requirements.

Existing tunable vacuum UV sources have been too weak to carry out traditional photochemical studies in the VUV, although some studies using atomic resonance lines have been possible. Consequently the photochemistry of the excited states of single bonds and of Rydberg states is almost completely unknown. Chemical analyses of photoproducts are often feasible with photon fluxes of 10^{12} per sec. Thus, even at the high resolution required for state-specific excitation in gases, such studies could be performed using the ALS.

ALS intensities are sufficient to produce detectable quantities of molecular hydrogen in single vibration-rotation levels of several excited electronic states. Rotational, vibrational, and electronic energy-transfer processes that occur in collisions may be studied. This is possible since, even at pressures of many Torr, VUV fluorescence quantum yields are still near unity. With an excitation intensity as low as 1 photon per pulse within the 1 cm^{-1} bandwidth of a hydrogen absorption line, count rates of tens of photons per second of rotationally resolved fluorescence can be expected. With one to two orders of magnitude higher intensity, rotation-vibration-electronic state-selected excitation of molecules such as HCN could be achieved. In this case, state-selective detection of the CN photofragments could be carried out using laser-induced fluorescence.

For work at very low pressures, such as those encountered in molecular beam experiments, the ALS output intensities will be marginal or worse for most spectroscopic and state-selective photoionization detection schemes. Such methods will become generally applicable only with a photon flux of 10^{16}/sec with a $\Delta\lambda/\lambda$ of 10^{-3} or less.

One area in which the ALS is totally unique is its ability to produce picosecond pulses of continuously tunable VUV radiation. Such a source will clearly find broad application in the study of condensed-phase reactions in non-VUV-absorbing solvents, e.g., rare gas liquids, and in allowing existing detection techniques such as photoionization to be extended into the picosecond domain.

Concluding Recommendations and Remarks

1) ALS clearly provides great opportunities for exciting new research using VUV photons. 2) The intensities available from the ALS will constrain the general applicability of the ALS in the study of low density samples and low probability reaction pathways. In the near term, it is thus expected that much of the most fruitful research with the ALS will involve using the ALS in conjunction with tunable laser sources. 3) A facility which combines the ALS with a VUV free-electron laser (FEL) offers such a powerful, generally applicable tool for exploring the chemistry of highly excited molecules that the development of a VUV FEL should be a high-priority component of the ALS initiative.

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6 Report of the Working Group on Applications of High-Spectral-Brilliance Synchrotron Radiation*

Introduction

This working group discussed the applications of high-spectral-brilliance synchrotron radiation in science and industry. Sub-groups discussed and made summaries on (1) spatial-resolution, element-sensitive x-ray imaging in 2- and 3-dimensions (microscopy and holography), (2) the application of x-ray probing to micro- and macro-biological systems, (3) the application of phase-sensitive x-ray measurement techniques to various aspects of materials properties, structure, and growth, and (4) the industrial application of x-rays, including research activities in support of x-ray lithography. Specific conclusions were reached with regard to ALS operation and performance and requirements for the ALS beam lines. The working group also recommended that NCAM support the ALS by developing optical elements useful in the energy range between 100 and 3000 eV.

Soft X-Ray Imaging

Introduction

The ability to image atomic assemblies, such as organic molecules, polymers, biological macromolecules, organelles, cells, metals, amorphous solids, composites, and fabricated microstructures, at atomic or near-atomic resolution is a basic ingredient of science today. It first became possible in 1913, when W.L. Bragg showed how to use the medium-energy x-ray photon (wavelength roughly 1.5 Å) for this purpose, creating the technique of x-ray diffraction analysis. In the 1930s a second imaging particle, the 50–100 keV electron, came into use with the electron microscope. These two particles remain the workhorses of high-resolution imaging to this day. Now a third major imaging particle, the soft x-ray photon (roughly 20–50 Å), appears ready to come into use. Impetus for the new particle is due in part to the increasing size and complexity

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of the atomic assemblies of interest in science, and in part to recent technological developments in the production and handling of soft x-ray photons. Imaging techniques using the soft x-ray photon include contact imaging, Fresnel zone-plate imaging, scanning microscopy, holography, and forms of diffraction analysis.

X-ray diffraction analysis and electron microscopy are subject to certain limitations outlined here. In both cases, limitations arise from the need to subject the specimen to special preparation techniques before imaging can occur.

In the case of diffraction analysis, the rather low reaction cross-section of the 1.5 Å photon makes it necessary to pre-assemble a large number of the atomic assemblies—microobjects—of interest into a macroscopic specimen. For the best imaging, it is necessary for the macrospecimen to be highly ordered, i.e., a crystal. As the microobjects of interest become larger, however, it can become difficult or impossible to obtain the supply of identical microobjects necessary to form a crystal (e.g., biological cells are not sufficiently identical to crystallize), and the assembly cannot be imaged with the desired quality.

In the case of electron microscopy, the opposite problem arises, making it necessary to disassemble large microobjects before imaging, e.g., by sectioning. Contrast-enhancing preparation usually is also required with low-Z (biological) materials because all low-Z elements have generally similar electron cross-sections; this preparation usually involves either removal of all water and the addition of high-Z staining atoms, or complete replacement of the microobject by a high-Z replica.

Despite these limitations, both x-ray diffraction analysis and electron microscopy are superb techniques. They have made and will continue to make contributions of inestimable value in science. Even if soft x-ray imaging should for some reason fail to develop, the older techniques will still keep scientists in the application areas of microobject imaging busy for years to come.

The soft x-ray photon has several properties that make it a promising microprobe. However, the wavelength range (20 to 50 Å) of these particles inherently limits the imaging resolution to 10 Å or more. Thus, the soft x-ray photon will never achieve atomic-resolution imaging. However, this limitation may be acceptable in many cases, especially when very large assemblies of atoms are being imaged, as in biological or materials studies.

Perhaps the most important property of the soft x-ray photon in considering its imaging characteristics is the fact that its reactivity lies between those of electrons and hard x-rays. Its penetration is virtually ideal for examining microobjects in the 1-μm thickness range, and can be adjusted upward and downward by lowering or increasing the wavelength. Assembly and disassembly operations on microobjects therefore are not required normally.

In addition, the rich absorption-edge structure (E,Z) in the wavelength region of interest makes it possible to obtain contrast by wavelength adjustment alone, without the use of chemistry, even with low-Z materials. In particular, water can be rendered transparent, and thereby can be left in place in the specimen, by working on the low-energy side of the oxygen absorption edge at 23.3 Å.

Further characteristics of the particle include the following. Its dominant reaction in matter is photoelectric absorption, i.e., the disappearance of a photon in an atom. This reaction gives rise to coherent scattering and thereby to diffraction, with its immense advantages in terms of the invertibility of the scattering problem.

In addition to the absorption reaction, the elastic-scattering reaction employed in standard x-ray diffraction analysis also carries into the soft x-ray region. This circumstance makes it possible to obtain information concerning the local elemental composition at a point of a specimen by observing the relative amounts of the absorption and scattering occurring there.

The predominance of the photoelectric absorption reactions carries a penalty in terms of radiation damage to the specimen: the imaging photon's entire energy of several hundred eV is deposited in some atom of the structure, with large attendant damage to the bonding structure in the region of that atom. Nevertheless, the energy deposition with soft x-ray photons is normally less in low-Z specimens than with electrons, because many fewer photons are required to obtain the necessary contrast in the image. As further compensation, the photoelectric absorption avoids the multiple-scattering problems of imaging with electrons.

In summary, although the soft x-ray photon is probably not quite the perfect imaging particle for large atomic assemblies, it is nevertheless a remarkably suitable one. Let us be grateful for it and put it to its intended use.

Imaging Techniques with the Soft X-Ray Photon

Contact imaging is probably the simplest technique and certainly the one that has been brought to the furthest point to date. The specimen is placed in contact with an ultrahigh spatial resolution x-ray detector. When x-rays pass through the specimen an image—the shadow of the specimen—is formed in the detector. X-ray photoresists with spatial resolutions of the order of 50 Å are the detectors used at present. After development, the image is enlarged by viewing in an electron microscope. The virtues of the contact technique are its simplicity, its resemblance to standard electron microscopy (the x-ray imaging step can be thought of as a special form of specimen replication for the EM), its very high resolution with thin specimens, and its ability (when used with plasma x-ray sources) to capture stop-motion images on a nanosecond time scale. The disadvantages are a loss of resolution with thicker specimens (due to blurring of the shadow-image by diffraction), and the relatively low efficiency of x-ray photoresists.

Fresnel zone-plate imaging closely resembles standard optical or electron microscopy, except optical or magnetic lenses are replaced by Fresnel zone-plates which serve as lenses for soft x-rays. The fabrication of the extremely small zone-plates needed for x-rays is a major technological challenge, but zone-plates giving approximately 600-Å-resolution images in this mode have been realized (Schmahl, et al., Göttingen), and further progress is certain.

A related technique is *scanning x-ray microscopy* (Kirz, SUNY Stony Brook; Schmahl, Göttingen). Here the Fresnel zone plate is used to form an x-ray microprobe, under which the specimen is scanned. Advantages of the scanning technique include minimal x-ray dosage to the specimen and the ability to combine spectroscopic techniques such as x-ray fluorescence and edge-structure analysis with the microscopy. The principal disadvantage is the currently lower resolution (compared with contact imaging) and the comparatively slow imaging obtained with present instruments.

Proposals have been made for reflection optics instead of zone-plate optics in the above techniques, using normal-incidence mirrors with multi-layer reflection coatings (Spiller, IBM; Haelich, DESY). Work on grazing-incidence reflecting systems is also in progress (Aoki, Tokyo).

The above techniques are all basically two-dimensional imaging techniques. However, the soft x-ray photon cries out for use in three-dimensional imaging, where its ability to deal with very large assemblies of up to 10^{12} atoms or more can be exploited fully. X-ray stereo images are obtained routinely in the contact technique, and are obtainable also in the other two-dimensional methods, but work is now beginning on techniques capable of true three-dimensional imaging: soft x-ray holography (Aoki and Kikuta, Japan; Solem, LANL; Chapline, LLNL; Howells, BNL; Kirz, SUNY Stony Brook) and soft x-ray diffraction-pattern analysis (Sayre, IBM).

For true three-dimensional imaging both of these techniques require exposures at many specimen orientations. Alternatively, both may be used in a single-orientation mode that gives lower resolution along the line of sight than in a plane perpendicular to the line of sight. They differ in their manner of determining the phase of the diffraction pattern of the specimen. The holographic technique of reference-signal addition has the advantage of being compatible with high-speed stop-motion studies in the single-orientation mode. The diffraction-pattern analysis method however, is probably the only one of the methods listed which is capable of reaching full theoretical resolution ($\lambda/2$) in imaging. By May 1983, several simple holograms and perhaps one diffraction pattern had been recorded at the NSLS at Brookhaven.

In summary, several of the two-dimensional imaging techniques with the soft x-ray photon are now operative, and work on three-dimensional techniques has begun. Diffraction, either in the specimen or in a fabricated structure is involved in all the techniques.

Beam-Line Requirements

X-ray imaging requires a high-intensity tunable beam line in the 200–600 eV energy range. Future developments in fixed-specimen imaging may bring a need for higher energy photons so planning should allow for an ultimate range of 100–3000 eV.

In terms of x-ray intensity, x-ray imaging calls for the specimen to be sufficiently illuminated to provide a statistically significant number of absorption events per areal resolution element. For example, for contact imaging this implies specimen illuminations of the order of 10^{13} photons/mm^2. The U-15 beam line at NSLS (bending-magnet source, single-grating monochromator) can meet this requirement with 1% bandwidth with exposure times of the order of 100 seconds. With an ALS undulator beam line, it should be possible to do contact imaging in the millisecond time range.

For the three-dimensional techniques, the beam line requirement becomes more demanding, especially in terms of spectral brilliance: useful illumination can be taken only within the spatial-coherency cone of the source and within the temporal-coherency energy slice required by the particular diffraction geometry involved. These requirements arise because the resolution elements must be counted three dimensionally (and hence are more numerous) while the probability of absorption must be replaced by the probability of large-angle coherent scattering (which is approximately 10^5 smaller). The result places the requirement for forming a full three-dimensional image at something like 10^{13} to 10^{15} coherent photons on the specimen, depending on size. After allowing for the size of the coherence cone at $\lambda = 30$ Å (approximately 10^{-5} mm^2 mrad^2) and assuming 1% efficiency in defining the energy window and bringing the photons onto a microscopic specimen, one concludes that the U_D beam line on the ALS may be able to provide the required exposure in 10^3 to 10^5 seconds. Although long, this exposure time might be acceptable in view of the very high image quality expected. With the U-15 beam line at NSLS, however, the exposure situation is hopeful only for the single-orientation mode of three-dimensional imaging.

With scanning microscopy the situation is intermediate, with coherence required but with absorption and two-dimensional counting of resolution elements still governing the required number of photons on the specimen. With an ALS U_D beam line a typical scan might be completed in approximately 1 second, provided that the scanning and counting could keep pace.

In terms of energy resolution, the different imaging techniques have different requirements. Contact microscopy is least demanding, and needs $\lambda/\Delta\lambda \sim 50$, whereas other microscopy techniques require $\lambda/\Delta\lambda \sim 200$. The three-dimensional imaging methods, however, have extremely stringent requirements for $\lambda/\Delta\lambda \sim 200^\circ$. Thus, although all the techniques use radiation in the same energy range, the variable requirements in terms of energy resolution call for radically different beam-line optics. Contact microscopy could use simply filtered radiation from undulator U_D, while the other methods call for a monochromator with accessory optical elements. To accommodate these different requirements, we suggest that the beam line for undulator U_D have several branches, at least one of which bypasses the monochromator. Each of the branches might contain optics specifically suited to the application.

To summarize, for high-resolution three-dimensional imaging the high-brilliance undulator source at the ALS is virtually a necessity. The two-dimensional forms of imaging can be done at existing synchrotron radiation sources, but at the price of a large increase in exposure times.

Other requirements for soft x-ray imaging include having at or close to the beam line:

1) A modest wet chemistry and biology laboratory, for preparation and preservation of short-lived biological specimens.
2) Optical and electron microscopes for examining specimens, contact images, holograms, etc.
3) A darkroom, for developing silver-halide emulsions used as holographic and diffraction-pattern detectors.
4) Some digital image-processing equipment.

A program should be initiated at NCAM to develop the non-standard x-ray optical components, especially ultrathin windows, microfabricated pinholes, and diffracting structures (zone plates, reference-wave generating structures, etc.), required for x-ray imaging. The microfabricated objects go *well beyond* normal microlithography standards in terms of resolution and precision of placement. Experience to date indicates the importance of having the imaging facility supported by a well-equipped microfabrication laboratory that is interested in the challenge posed by the optical devices. In return, the x-ray experience will feed back invaluable data to the microfabrication laboratory.

Finally, it is desirable, in a scientific program on x-ray imaging, to set up serious cooperative research programs with biologists and materials scientists, with each program seeking to bring to bear one or more specific capabilities of x-ray imaging onto an important problem in the field. We recommend holding workshops to select research topics and specimens carefully. Such an approach is simultaneously the best way to develop the technique along useful lines, and to help scientists in the other fields assess the usefulness of the technique and learn its technical aspects.

Biological Applications

Introduction

Biological applications pursued successfully on synchrotron radiation sources include both microscopic examinations of tissues and organisms and clinical, macroscale biology. The brightness and the time structure of the ALS make it an extremely attractive source for continuing and expanding these studies. Before mentioning specific applications and their requirements, however, the working group wants to emphasize several general recommendations that will go a long way toward making the ALS useful to biologists.

1) The ALS must be very user friendly to be useful to biologists not accustomed to dealing with huge accelerators or specialized x-ray equipment. Support staff are essential to handle the hassles of hooking biological experiments up to beam lines and assuring that the monochromators, mirrors, and other optical elements are set correctly.

2) The features and advantages of synchrotron radiation, in general, and the ALS, in particular, must be brought to the attention of biologists.

3) Working groups should be organized to identify key biological problems that might prove tractable by synchrotron radiation techniques.

4) Clinical applications, such as angiography, should be pursued and, if they are promising, dedicated beam lines operating year-around should be set up with experimental chambers that don't intimidate patients.

Synchrotron radiation has made the soft x-ray portion of the spectrum a valuable probe of biological materials. The advantages of synchrotron radiation are that it is continuously tunable, it is bright, it is pulsed, and that photons are less destructive of specimens than electrons, neutrons, or ions. Furthermore, the interior of moderately thick samples can be viewed without cutting or staining, and compositional variations within the tissue can be studied by selecting photon energies near the K edges of biologically interesting elements, such as carbon, nitrogen, and oxygen. With its extreme brilliance and short pulses, the ALS may make it possible to study ongoing biological processes in additional to biological structures.

Microscopy

There are several ways in which soft x-ray microscopy can fill a definite need in biological structure research. The ability to image chemical elements, opportunities to explore the connective properties of cell structure, and the unique high-contrast modes make the soft x-ray imaging technique very attractive.

Work already done utilizing non-synchrotron x-ray sources suggests that x-ray microscopy has the potential to make valuable contributions to the study of biological materials. A variety of cell types, prepared in different fashions, have been examined with contact x-ray microscopy, in which a replica of the photon absorption characteristics of the specimen is made by exposing a photoresist to soft x-rays. Direct comparison of specimen images produced by electron scattering (in conventional electron microscopy) and by photon absorption has shown that photons highlight cellular structures not readily visible with electrons.

A soft x-ray beam line capable of exploiting this potential should have the following characteristics:

1) Appropriate vacuum barriers to permit resist exposures, probably utilizing thin windows and differential pumping.
2) A monochromator with the capability of tuning through absorption edges of elements common in biological materials (range 100–1500 eV), and with a resolution ≤ 5 eV. The elemental analysis possible with contact images obtained above and below the absorption edges of these elements should prove extremely useful in determining the function of cellular structures.

3) In order to permit observation of wet specimens, there should be sufficient photon fluence at the output point to expose a PMMA-based resist in approximately 1–100 msec (i.e., ≥ 0.1 J/cm^2 delivered at 400 eV over a total area of at least 1 mm^2).

In addition, information on the real needs of biological research should be considered early in the design of insertion devices, beam lines, and experiment chambers for the ALS.

The role of soft x-ray microscopy should be evaluated particularly with respect to currently available microscope technology (high-voltage electron microscopy, scanning electron microscopy with characteristic x-ray signal, freezer-etch techniques in electron microscopy, etc.). It is important to make every effort to match the characteristics of soft x-ray microscope systems to the *real* problems that must be overcome with respect to currently available microscope technology and to be sure that we are trying to provide a new microscope technology that answers some of the important questions being asked by structural biologists.

Macrobiology

The capability of synchrotron radiation to monitor composition variations within tissue has produced at least one clinical technique for looking at large specimens that seems quite successful. The safe, noninvasive technique images the human heart to diagnose coronary artery disease. A small dose of iodine, injected into the patient, becomes distributed throughout the blood. By illuminating the patient's chest with two different wavelengths (around 33 keV) bracketing the iodine K edge, the distribution of iodine and thereby the condition of the arteries within and around the heart, can be seen.

The technical requirements are for a sufficient flux of photons at 33 keV and a beam of the appropriate width. The superconducting wiggler (W_F) planned for the ALS should produce a beam, when the storage ring is operated at 1.9 GeV and a wiggler field of 5 Tesla, that nominally meets those requirements. The width of the central beam is 15 cm at 14.7 meters from the source and therefore in excess of 30 cm at the experiment station. The available flux at 33 keV, integrated over the vertical emission angle, is shown in the table in comparison to the flux available or projected from SSRL, NSLS and SRS. If SSRL, where studies of coronary angiography are presently most advanced, is used as the figure of merit, then comparable studies should be possible at ALS.

Table

33-keV Flux from existing and planned synchrotron radiation sources in the United States

	GeV	Kg	mA	ϕ sec^{-1}mm^{-1}
SSRL	3.0	18	100	2.1×10^{10}
NSLS	2.5	60	500	1.7×10^{11}
SLS	2.0	50	400	1.1×10^{10}
ALS	1.9	50	400	1.8×10^{11}

Si(220), 20 meters

Angiography studies are presently either underway or projected at SSRL, DESY and NSLS. A clinical evaluation should occur at one or more of these laboratories in the next 2-3 years. If the method is successful, there will be widespread interest in exploiting it. This will be most attractive and feasible at dedicated rings such as the ALS, especially when they are situated in large population centers and operate continuously throughout the year.

For this application alone, the development of the projected wiggler-F beam line at ALS, and especially the central portion of this beam, would be worthwhile. There should be considerable application for such a beam line to clinical medicine, in both research and diagnostic areas. The development of other clinical applications of monochromatic x radiation should also be anticipated. It is probable that many current radiological procedures could benefit from monochromatic sources, some in perhaps critical ways. Eventually, it is desirable to develop a monochromator system that is capable also of scanning the x-ray beam vertically while the patient remains stationary.

X-Ray Lithography

Introduction

The need for an alternative to optical lithography for manufacturing integrated circuits probably will occur in the 1990's to achieve a feature resolution of 0.5 μm. Electron-beam systems will be needed to make masks but will not be cost effective for high volume production in direct-write mode. Synchrotron x-ray sources likely will become the preferred tool for mass production of integrated circuits.

Several technological problems must be solved before x-ray lithography can be employed industrially to manufacture electronic devices. The technology for making an x-ray absorbing mask on a thin x-ray-transparent, dimensionally stable support is probably the most important problem. Another problem involves optimizing simultaneously the source power and the resist sensitivity. Mechanisms for aligning the devices automatically during the exposure must be developed. Finally a technology is needed for creating large (several square centimeters) high transmission windows to withstand the large pressure difference between the evacuated beam line and the lithography chamber.

Industrial Requirements

To accommodate a range of mask and resist materials, the spectral range for a lithography beam line should cover 3 and 20 Å. The intensity should be as high as the mask can tolerate—up to a few tenths of a watt at the desired wavelength. Since the energy resolution is not very critical and the intensity is critical, a 20%-bandpass filter is preferable to a monochromator. An undulator source appears promising, both in power output and in spectral-peak resolution.

The lithographic parameters required for industrial applications must also be considered as x-ray lithography facilities are designed. In light of fundamental limitations of the printing process, the goal of x-ray lithography should be to achieve 0.2 μm minimum feature size on a 25 mm by 25 mm field. The distortion of a mask of these dimensions should not exceed 500 Å (3σ). The mask should afford a contrast approaching 90%, and have line-width control of 500 Å (3σ) at edge angles greater than or equal to 80°. A step-and-repeat system or step-and-rotate system is desirable for moving the wafer to enable its entire surface to be printed (sixteen fields for a 4″ wafer). This stepping must be repeatable with a tolerance of 0.02 μm.

To protect the mask, the mask-wafer separation (gap) should not be lower than 20 μm. Gap control should be ±1 μm. (Magnification compensation of process-induced linear distortions of the wafer cannot be achieved at this point except by tailoring the mask to the process). The wafer-to-mask alignment must be achieved in a dynamical fashion, continuously monitored (by optical or other means), and maintained to 500 Å (3 σ). Mask level-to-level alignment must have the same accuracy.

X-ray Lithography Facility at the ALS

An x-ray lithography program should aim to optimize simultaneously all the technological variables, from source features, to mask technology, to resist development, to sample handling. For this purpose the ALS, with nearby Laboratories for resist processing and mask development, would be a suitable experimental facility.

The Advanced Light Source should serve as a flexible x-ray lithography source as well as a vehicle for exploring new lithographic approaches that exploit the capabilities of undulators. A systems approach to x-ray lithography should start with the design of the accelerator itself. For lithographic purposes, high photon flux and a wide horizontal angle would be desirable. An undulator source would be very promising if the x-ray optics could scan a power of 1 W over several square centimeters by means of the x-ray optics.

All wavelengths in the 3 Å to 20 Å region should be obtainable, so that the ALS can simulate a conventional source as well as demonstrate the capabilities of synchrotron radiation. As a simulator of conventional sources, the ALS will support and be a test bed for technological improvements applicable to such systems. Source and optics development for two suitable insertion-device based beam lines might cost as much as $4M. This includes a lithography wiggler, cold mirror, and window for 20% bandwidth selection. It also includes a lithography undulator with cold mirror and window to serve the 15 Å region. Both of these sources will have to be scanned to cover the exposure area at a uniformity of ±3% with 1-mrad maximum divergence angle. It will also be necessary to build a large, thin window with back-up vacuum protection. Some the required advanced optics development could be pursued to advantage at NCAM's reseach laboratories.

An exposure chamber should be built with filter, shutter, mask and wafer holder, and cooling-gas apparatus. IT should be possible to scan the wafer during an exposure and to step it between exposures. Instrumentation to monitor both photon flux and wavelength is also needed, and can probably be obtained for $1M. An alignment system capable of dynamic (during exposure) alignment should also be included. It may be possible to purchase such an alignment stage and incorporate it into the exposure chamber for $1M.

A dedicated support laboratory for processing resists should be readily accessible ($1M). Here resist could be spun on wafers, baked, developed (including dry etching), and inspected with a low-voltage SEM. A rudimentary mask technology should be made available through cooperation with vendors. Provisions should be made to incorporate alignment marks for the alignment system and to adapt to standard industry mask sizes ($500K).

SSRL Lithography Program

The lithography program at SSRL includes research on photoresists, x-ray optical elements, and source development. The beam line is shared with microscopy users and uses radiation from a bending magnet. The horizontally deflecting mirror has a 0.6 mm acceptance, and a windowless differential pumping system separates the poor vacuum (10^{-6} Torr) in the exposure station from the 10^{-10} Torr vacuum in the storage ring. The system delivers a beam with a size of 2 × 8 mm^2. A Si(III) channel-cut crystal serves as the monochromator, and the resist-covered wafers are held on a linear-motion feedthrough.

Plans for 1983—85 include improvements to both the monochromator and the exposure station. The monochromator will use synthetic, layered microstructures as the diffractive elements and will cover the range from 500 eV to 4 keV with a 10% bandwidth. The exposure station will be modified to accommodate commercially available x-ray masks and have a pumping system which will allow for rapid pumpdowns. This modified system should be in use by early 1984.

Plans for 1986—1987 will be directed towards making the source compatible with practical lithographic exposures. To do this, the differential pumping system will be replaced by a thin window to both allow for the use of a large beam (3 × 3 cm^2) and a He atmosphere in the exposure station for heat sinking of the mask. The beam will probably be scanned in the vertical direction to achieve the desired beam height. The horizontal size would be achieved by increasing the size of the deflecting mirror to accept 2.5 mrad of the radiation coming from SPEAR. The anticipated cost of these improvements is about $250 K.

Improvements for 1988 and beyond will depend greatly on the interest generated in the beam line by outside users. If enough interest exists, mask-to-wafer alignment capability as well as a clean room and some processing facilities would be added along with the appropriate staffing to operate such a facility.

X-Ray Interference Effects

Reaching beyond the more usual use of x-ray intensity and spectral features, it is becoming possible to utilize x-ray phase effects in the study of materials properties, surface formation and structure, etc. Proposals at the workshop included the use of natural diffracting crystals and synthetic multilayer reflectors to study phase modifications in interferometers, Fabry-Perot etalons thin-film-coated crystals, etc. The approach would permit highly detailed studies of anomalon dispersion by independently measuring real and imaginary parts of the atomic scattering factors of materials. Polarization and chemical bonding effects would also be studied.

The use of standing x-ray wave patterns in the vicinity of interferometric surfaces could be used in studies of lattice deformation, solid-solid interface structure, location of impurity atoms, etc. For such studies to be performed one requires a stable, reliable source of x-rays, tuneable over a range extending from 100 Å to values approaching 0.1 Å. Harmonics of the primary wavelength must be rejected.

In order to extend these phase-sensitive studies to the sub-keV region, new optical elements will be required. For this purpose, multiplayer fabrication technology should be developed at NCAM to synthesize thin films (few atomic planes) on interferometric and Bragg diffraction surfaces. The requisite multilayer mirrors and monochromators must be exceedingly high quality to permit these very sensitive standing-wave materials studies. Workshop participants noted that the same multilayer-synthesis requirements are also important to microscopy, holography, and general x-ray transport techniques discussed previously in this section.

7 Report from the Working Group on Free Electron Lasers*

Introduction

The ALS will be the most powerful source of broad-spectrum, incoherent radiation in the world. The working group suggests that this capability be augmented with a parallel program of research and development on coherent sources. There is no single source of coherent radiation for the entire eletromagnetic spectrum. Some sources can be built now, others might be built in the near future, and some are only "hopes", but constitute valid goals for a research program which would stretch over many many years.

The group generalized its charge to include:

1. Any source of coherent radiation for the ALS complex;
2. Any devices, not just within the ALS complex, which are advantageous as coherent radiation sources.

Recently, the Free Electron Laser Subcommittee of the Solid State Science Committee of the National Research Council reviewed the status and value of free electron lasers (FELs). They concluded that FELs were extremely promising sources of coherent radiation in two wavelength regions, the far infrared ($\lambda > 25\ \mu m$) and the vacuum ultraviolet ($\lambda < 200$ mm). In these ranges, the free electron laser has a huge potential for catalyzing major scientific advances. However, the strategy and design of a VUV FEL differs greatly from that of a FIR FEL.

To meet its charge, the working group considered the three U.S. projects on FIR FELs: (the Shaw-Patel device under construction at Bell Labs, Madey's proposal at Stanford, and Elias' device under construction at UC-Santa Barbara). In addition, Great Britain has a FEL project (FELIX) at Daresbury to address the spectral range between 150 μm to 5 μm, and Reinieri is building a device to operate at 15 μm at Frascati.

In the VUV range, there are two devices under construction in this country: the BNL-FEL in the NSLS-VUV Ring (under construction), and the optical-klystron (frequency multiplying device) of Bell Labs to go at BNL.

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*A.M. Sessler (LBL): Chairman, D. Deacon (Stanford), L. Elias (UCSB), B. Kincaid (Bell Labs), R. Klaffky (BNL), J. Madey (Stanford), D. Prosnitz (LBL), E. Shaw (Bell Labs), J. Wurtele (LBL).

In other countries, at least three VUV FELs are being installed at synchrotron radiation sources. These include Adone at Frascati, DCX at Orsay, and VEP3 at Novosibrisk.

The detailed proceedings of this working group appear in a separate publication, "Report of the Working Group on Free Electron Lasers at the ALS/SSRL Users Workshop," (LBL Pub. 5096).

Recommendations

After surveying the various programs in the US on FELs, the group felt that a program of R&D on sources of coherent radiation would naturally complement the ALS.

There is a need for good IR sources and, also, for coherent sources in the VUV. Even in the part of the spectrum covered by lasers, new sources could make important contributions. Such sources must be evaluated on the basis of line widths, stability, reproducibility, peak power, tunability, efficiency, average power, and, finally, convenience and cost. Even, for example, in the range served by dye lasers a high-peak-power device would be novel and hence of interest for a multitude of applications.

In the IR, LBL should pursue development of a single pass device, very similar to that which Earl Shaw & Patel are building at Bell Laboratories.

In the range from 1,000 Å to 2,000 Å Bell Laboratory is building a frequency multiplying device to operate on the VUV ring at NSLS. The longer straight sections of the ALS are suited to an improved second generation version of such frequency multiplying devices (optical klystrons).

It was felt that a VUV-FEL similar to the FEL at the NSLS should be built into the ALS. Unfortunately, the FEL would perform optimally only when the ALS operated at 500 MeV. Since these operating conditions are not favorable for photon beam generation by wigglers, undulators, and bending magnets, probably a dedicated ring designed to run at 500 MeV should be built for the FEL.

The group felt there were other coherent sources which might complement the ALS, but in the limited time at its disposal concentrated on the above proposals.

Finally, it was noted that a great deal of work was needed before one could properly propose and design coherent source devices for the ALS. The group felt that a concerted attack on the topics listed below should be mounted at the earliest possible date so as to have available soon, detailed proposals for an IR-FEL and a VUV-FEL.

Topics for Study

1. Radiation from the ALS, in the IR, in the forward direction.
2. Inserts in the ALS (wigglers, many-bend magnets, undulators); i.e., how does radiation pattern depend on λ, λ_w, B, γ, N in the forward direction.
3. Is it advantageous (in the IR) to go to non-forward angles? If so, repeat (1) and (2). Anyway we need to know how the radiation depends on angle.
4. A single-pass (for the electrons) FEL in the IR (say 50 MeV electrons). For this we have two cases:
   (a) Use of the proposed ALS injector
   (b) A "new"—better matched for FEL use—injector for the ALS.

5. Design a FEL for one of the straight sections of the ALS. What is its performance? How does performance vary with energy?
6. Design an optical klystron (frequency multiplier) for the ALS. How will it perform? (A laser harmonic generator of coherent light in the VUV by using an optical klystron.)
7. Consider a special ring (say E = 300 MeV) optimized for FEL action. What is the performance of such an FEL? How much better is it than an FEL in the ALS?
8. What are the user requirements both in the IR and the VUV? Is there a preference for one kind of a device over another?

8 General Operations*

The provision of facilities for properly setting up and maintaining beam lines is nearly as important as the proper selection of monochromator designs and initial specification of optical elements. A large amount of money is spent for state-of-the-art optical components which require very precise alignment to achieve specified imaging properties. These optical elements are expected to operate at peak efficiency for months or years of service. An electron-beam steering error, a small bump to a mirror support, the build-up of contamination on optical elements, or a malfunction of a monochromator can lead to serious reduction in beam-line efficiency or; even worse, erroneous energy output from the beam line. It is therefore cost effective to provide means of in-situ testing, calibrating, realigning, and if possible, cleaning and recoating of beam-line components.

It should be possible to monitor the flux and energy output of a beam line and to gain enough information about the status of individual optical elements to take corrective measures when malfunctions are discovered. Means should be provided for measuring the absolute intensity of the beam, and a well-characterized series of samples, absorbers, and/or sources should enable quick and accurate energy calibrations. ALS beam parameters should be available in computer-readable form at each experimental station.

The small divergence and cross-sectional areas of undulator beams mean that mirrors and gratings will be fairly small, thereby permitting good possibilities for in-situ cleaning or recoating. Carbon contamination of optical elements continues to be a problem at existing synchrotron radiation sources. This problem is most severe in the soft x-ray region near the carbon K-edge, but it is still serious near 10 and 30 eV. In-situ ion etching or atomic oxygen cleaning may offer possible solutions to the problem. Atomic oxygen cleaning might be as simple as providing a controlled leak from an oxygen reservoir that maintains an oxygen partial pressure in the beam line (of the order of 10^{-9} torr in a beam line with base pressure $\leq 10^{-9}$ torr) in the presence of beam. Beam-disassociated atomic oxygen can then oxidize carbon deposited on optics, allowing it to be pumped away as CO.

In general, the monochromator is the most expensive part of a beam line. Since undulator beams have such small cross sections that it is difficult to run simultaneously two or more experiments on one undulator line, a substantial saving could be achieved by using a single monochromator on the undulator and diverting the beam between experiments after the monochromator. Mirrors might be employed to deflect the photon beam, as on the beam line WUNDER at SSRL,

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*Considerations from the VUV Working Group.

especially for VUV-only monochromators. Alternatively, some means of indexing experimental chambers into position after the monochromator exit slit could be devised. The alignment of a sample chamber switched in and out of the beam need not be time consuming, especially if the chamber *and* the associated electronics are moved as a unit. Both can be mounted on a warehouse-grade air bearing, and moved into position onto indexing mounts in the floor. We suggest this as a viable alternative to moving the exit beam from the monochromator, especially for energies above 30 eV. A standard exit-slit housing should be designed, after suitable user input, and a standard movable experiment platform would drop into a kinematic mount in front of the exit slit. The description of these should be promulgated to prospective users.

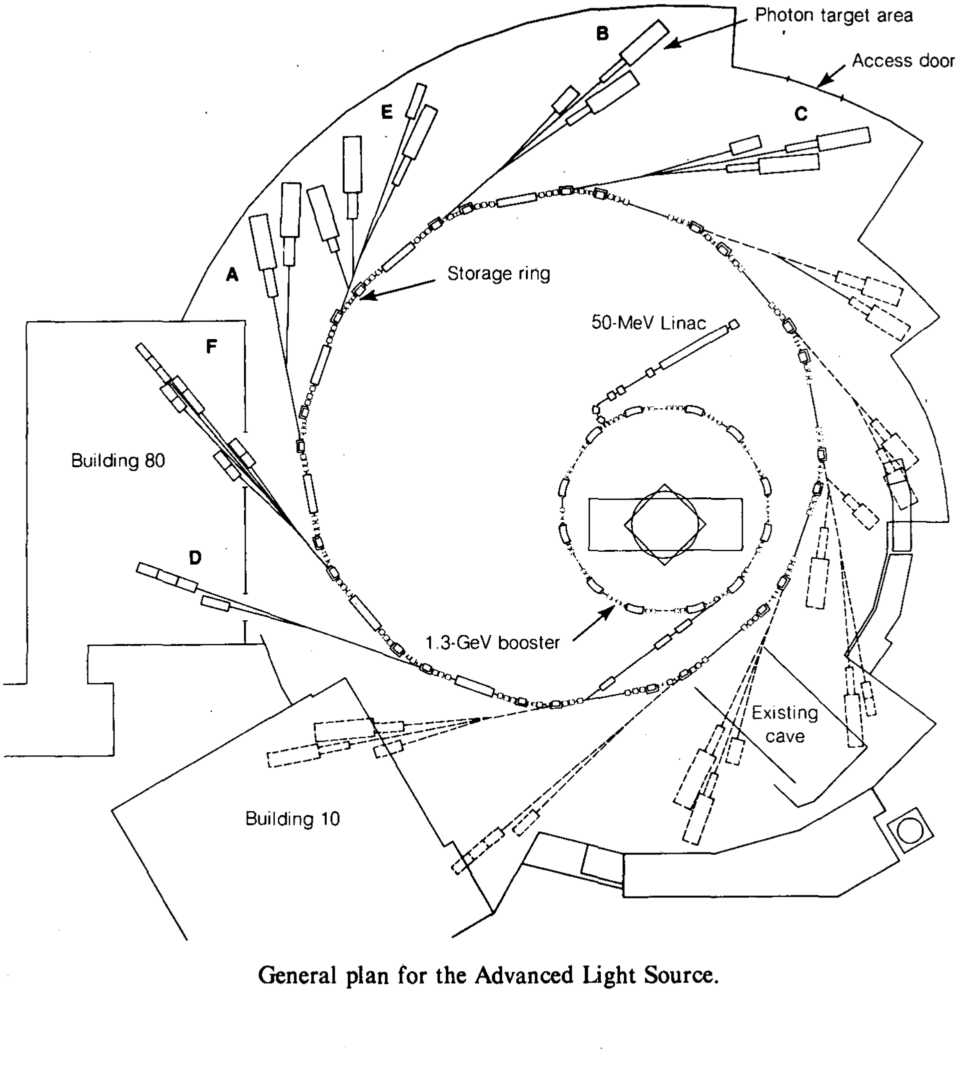
One or two general-purpose photoemission and perhaps photostimulated desorption sample chambers should be provided. These have proven to be very often used at SSRL, especially by short-term visitors (who often become repeat visitors). They should be designed in collaboration with scientists active in these fields.

We cannot overemphasize the need for high beam-positional stability. In some cases the beam will be imaged onto 10 μm slits, and the image must be stable in average position and not fluctuate about that average position. Beam motion is even more severe in some slitless configurations. Vibrations must be controlled, unless proven harmless. It is possible that the most sensitive monitor of beam stability is the output of a high-resolution monochromator. Thus, users complaining about beam instability must be listened to!

The use of the ALS in a few-bunch mode reduces the photon flux to all users. To maximize utilization, and for humanitarian reasons, the dedication of, e.g., one eight-hour shift per day, to the few-bunch mode should be considered, reducing the wear on users of all types. Similar considerations apply with undulators, and even wigglers. The setting of the insertion device parameters would be done by one "principal user" on each line. This may make the spectrum not useful to the "secondary users." Primary and secondary users may interchange every 8 hours or so, if possible. (The moving of a sample chamber precludes this mode of operation). The undulator parameters may have to be scanned, with a definite impact on others. Again some scheduling of these parameters should be considered.

Since ALS will be a user-oriented facility, there are a number of user needs not yet addressed. Laboratory and office space have been described in NCAM literature, as has an experiment-staging area. Short-term storage is a necessity, as are several clean work stations. The housing and parking situation must be addressed. The availability of low-cost (graduate students!) housing at all seasons of the year may be a problem.

Appendix 1. Advanced Light Source



General plan for the Advanced Light Source.

Introduction

The Advanced Light Source (ALS) is a synchrotron radiation source composed of a 50-MeV linear accelerator, a 1.3-GeV "booster" synchrotron, a 1.3-GeV electron storage ring, and a number of beam lines. The design of the ALS has been optimized to achieve two major goals: to provide intense photon beams in the energy range 0.1 eV to 5000 eV and to provide very short pulses (tens of picoseconds) of synchrotron light for the many experiments with timing requirements in this range. To meet these goals, the electron beam has a very small emittance, and the storage ring includes twelve long, straight sections for wigglers and undulators. These insertion devices simultaneously intensify synchrotron radiation and modify its spectrum. The ALS will take advantage of the photon-beam intensity and versatility of such insertion devices. In turn, the low electron-beam emittance will make it possible to optimize the performance of the insertion devices. All told, more than 30 photon beam lines will emanate ultimately from the ALS complement of twelve insertion devices—one per long straight section. Additional beam lines, especially to cover the spectral range 0.001 eV to 1 eV, will come from bending magnets.

The ALS has been the subject of an intensive design effort over the past year, including a technical review in January 1983 by synchrotron radiation experts from throughout the United States and abroad. There have also been two reviews by DOE's Office of Management looking into technical, cost, schedule, and other management concerns. For technical details about it and its components, please refer to Volume 1 of the NCAM Conceptual Design Report.

Major Parameters

The major parameters of the ALS can be understood best by making a comparison (see Table A1–1) with existing electron storage rings dedicated to synchrotron radiation. The most prominent feature of the ALS design is the large number of straight sections for wigglers and undulators. These special synchrotron-radiation sources will provide greatly enhanced photon-beam performance, as compared with bending magnets, and the required straight sections account for the relatively large circumference of the ALS. The second noteworthy feature of the ALS is the very small design value of the horizontal emittance of the electron beam. This emittance has been carefully minimized in the ALS design in order to maximize the intensities of the photon beams, in general, and to increase greatly the spectral brilliance of the undulator photon beams, in particular. The excellent performance of wigglers and undulators permits the selection of modest values for the electron energy and electron current, while maintaining outstanding photon-beam performance. Table A1–2 presents a more detailed list of parameters for the ALS electron storage ring. The selection of parameters is a process of compromising among competing, and often conflicting, design considerations.

The brilliance or intensity of the ALS photon beams can be quantified in two different ways. First, there is the quantity called "spectral brilliance," which is measured in the following units:

$$\text{Spectral brilliance} = \frac{\text{photons}}{\text{s} \cdot (\text{mm})^2 \cdot (\text{mrad})^2 \cdot (0.1\%\ \text{bandwidth})}$$

Table A1–1
Electron Storage-Ring Design Parameters

	ALS (Proposed)	Aladdin*	NSLS** (VUV)	NSLS** (X-ray)	SSRL† (SPEAR)
Electron Energy (GeV)	1.3 (1.9 max)	1	0.7	2.5	4
Electron Current (mA)	400	500	1000	500	100
Circumference (m)	182.4	88	51	170	234
Horizontal Emittance (10^{-8} πm·rad)	0.68	6	8	8	40
Bunch Length (ps)	35	80	400	400	100

*The storage ring at the University of Wisconsin near Madison.

**The National Synchrotron Light Source operates two storage rings located at the Brookhaven National Laboratory in New York.

†The Stanford Synchrotron Radiation Laboratory uses the SPEAR storage ring at Stanford, California.

Table A1–2
Advanced Light Source Design Parameters
(Electron Storage Ring)

Electron energy (GeV)	1.3 (1.9 max)
Electron current (mA)	400
Circumference (m)	182.4
Horizontal emittance (πm·rad)	6.8×10^{-9}
Number of superperiods	12
Number of long straight sections	12
Length of long straight sections (m)	6
Maximum horizontal beta (m)	13.3
Maximum vertical beta (m)	13.3
Horizontal tune	13.8
Vertical tune	7.8
Horizontal chromaticity	–32.0
Vertical chromaticity	–17.5
Energy loss per turn —dipoles only (keV)	64
Radiofrequency (MHz)	499.65
Harmonic Number	304
1.9–GeV Operation:	
Dipole field (T)	1.60
Maximum quadrupole gradient (T/m)	22.9
Energy loss per turn—dipoles only (keV)	291

This quantity is the spectral intensity of the radiation divided by the phase-space volume into which the radiation is emitted. (The phase-space volume is the product of the cross-sectional area of the electron beam, measured in square millimeters, and the solid angle of the cone of radiation, measured in square milliradians.) For experiments that require the synchrotron radiation to originate from a small volume in phase space, spectral brilliance is a figure of merit for photon intensity.

A second useful measure of photon intensity is the photon flux, defined as

$$\text{Photon flux} = \frac{\text{photons}}{\text{s} \cdot \text{mrad } (\theta) \cdot (0.1\% \text{ bandwidth})} \quad \text{for all } \psi$$

This quantity is the spectral brilliance integrated over the following three variables: the electron-beam width, the electron-beam height, and the vertical angle ψ. Note that the photon flux is still a differential quantity with respect to the horizontal angle θ.

Figures A1–2 and A1–3 show the average spectral brilliance of the ALS photon beams for an electron current of 400 mA. The spectral output of undulators consists of a number of sharp peaks. Thus, Figure A1–3 shows smooth curves drawn through the maxima of the spectral peaks for each undulator. The top curve in Figure A1–2, however, is the envelope of the curves in the following graph. For all ALS and NSLS curves in Figure A1–2, the electron beam vertical emittance was assumed to be one-tenth the horizontal emittance. Since the undulator spectra consist of peaks, it is necessary to vary the undulator fields to scan over all desired photon energies. For undulators constructed with permanent magnets, the field strengths are varied by changing the magnet gaps. The label "average spectral brilliance" means that the spectral brilliance has been averaged over time, i.e., the small duty factor of the electron beam has been ignored. While an electron bunch traverses an undulator, for example, the instantaneous spectral brilliance is much higher than is shown in these figures.

To compute the spectral brilliance introduced above, one starts from the following quantity

$$\text{Spectral brightness} = \frac{\text{photons}}{(\text{s})(\text{mrad})^2(0.1\% \text{ bandwidth})}$$

This quantity is unambiguously determined from electromagnetic theory. The spectral brilliance is then obtained by dividing the spectral brightness by an effective source area S, which is given by

$$S = 2\pi\Sigma_x \Sigma_y \ , \quad \Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + (\lambda L + \sigma_{x,y}'^2 L^2)/4}$$

in the case of a wiggler or an undulator of length L. Here, $\sigma_{x,y}$ and $\sigma'_{x,y}$ are the one-standard-deviation sizes and angular divergences of the electron beam, and λ is the wavelength of the observed photon. S is a measure of the effective source area including the effects of diffraction and the extended nature of the source (i.e., depth-of-field effects). However, it should be mentioned that the definition of S is somewhat arbitrary, and different authors use different numerical factors. For a bending-magnet source, both the diffraction effect and the depth-of-field effect can be neglected (except in the far-infrared region) so that

$$S = 2\pi\sigma_x\sigma_y \quad .$$

Figure Al–3a shows the photon flux from the bending magnets at the ALS and the much higher photon fluxes from the ALS wigglers. Note that a superconducting wiggler magnet can provide photons with energies up to about 40 keV.

The theory of electron storage rings has not been developed to the point that it can predict with certainty the peak operating parameters that can be achieved with a storage ring. Nevertheless, this section presents the approximate parameters for a few ALS standard operating modes. The "initial performance goals" which are given in Table Al–3 represent the state-of-the-art performance as scaled from existing storage rings, and these figures may be used as a general guide by prospective users of the ALS. The peak currents in this table can be used to calculate instantaneous spectral brilliances and photon fluxes from Figures Al–2 and Al–3a, which show curves for 400 mA average current. The "ultimate performance goals" represent some extrapolation from current experience, and they should not be used to plan synchrotron radiation experiments at this time. However, these ultimate goals are consistent with presently understood limits on storage ring performance, and it is the firm intent to design the ALS so that it can be operated at these conditions.

Injection System

The injection system for the ALS consists of a 50-MeV electron linear accelerator and a 1.3-GeV booster synchrotron. High-energy injection into the storage ring was chosen to minimize any possible interruptions to experiments caused by the filling process. Under typical operating conditions, the beam lifetime will be about 8 hours, and it will take between 3 and 10 minutes to refill the storage ring. Injection at the normal operating energy will also help to avoid small but disruptive changes in the beam-spot position that can be produced by energy ramping.

The electron linear accelerator is a 50-MeV S-band linac about 8 m long. It can deliver up to 50 mA, with a small duty factor. The electron beam from the linac is modulated or chopped to provide the required time structure to fill the rf buckets in the booster synchrotron. The use of different operating modes permits varying the number of electron bunches in the booster and in the storage ring.

The booster synchrotron accepts the 50-MeV beam from the linac, accelerates it to 1.3 GeV, and transfers it to the storage ring. The booster cycles at 1 Hz, with each cycle consisting of a 0.35-s accelerating ramp, a 0.2-s flat top to allow the beam to damp completely, a 0.35-s descending ramp, and a 0.1-s quiescent period.

The lattice of the booster synchrotron is similar to the lattice of the storage ring in that it is made up of a series of achromatic cells with intervening straight sections. The circumference is 67.2 m (7/19 of the storage ring circumference). This lattice was chosen over other possibilities because it has the following advantages: convenient injection and extraction, low emittance, low dispersion, high superperiodicity, adequate space for control and monitoring equipment, and efficient use of space. These advantages minimize the requirements for the injection and extraction magnets, the apertures, and the rf voltage. They also permit the booster to be located conveniently within an existing building.

Table A1–3
Approximate Parameters for
ALS Standard Operating Modes

Energy (GeV)	0.9	1.3	1.3	1.3	1.9
Number of Bunches	250	250	20	4	250
Initial Performance Goals					
Average current (mA)	400	400	200	30	400
Bunch length (ps)	23	23	38	35	27
Peak current (A)	34	34	128	104	29
Ultimate Performance Goals					
Average current (mA)	400	400	400	200	400
Bunch length (ps)	23	23	50	90	27
Peak current (A)	34	34	194	270	29

The booster can be operated in several modes. In the various modes, the time to fill the storage ring to 400-mA ranges between 2.5 and 5 minutes, assuming a 50% overall transfer efficiency.

Photon Beam Lines

The ALS is an electron storage ring with characteristics—low emittance, short bunches, and long straight sections—that permit great flexibility in the design of photon beam lines. The photon beams can derive from bending magnets or from insertion devices (wigglers and undulators) placed in the long straight sections. Altogether, the ALS has 12 long straight sections, so 12 insertion devices can be accommodated. Initially, however, a complement of only six insertion devices (probably four undulators and two wigglers) is planned. The specific insertion devices will be selected over the next several months on the basis of advice from the users of the facility. For the sake of estimating the cost and performance of the ALS, however, a provisional set of six insertion devices has been proposed. Figure A1–1 summarizes the properties of these devices.

To use the synchrotron radiation efficiently, several photon beam lines can be built to use the radiation from a single insertion device. The six initial insertion devices, for example, can accommodate up to 19 photon beam lines. Present plans call for constructing fourteen of these beam lines during the start-up phase of the ALS. Final plans for the experimental areas and beam lines will be made in consultation with the users of the facility.

Figure A1-1. Summary of Currently Planned ALS Insertion Devices (1.3 GeV).

Name	Insertion Device Type	Peak Field (T)	Period (cm)	No. of Periods	Length (M)	E (eV)
U_A	Permanent magnet undulator	0.29	16.7	30	5	8-200
U_B/U_C	Hybrid undulator	0.54	5.0	100	5	75-3000
U_D	Hybrid undulator	0.57	3.5	142	5	200-5000 (up to 10000 at 1.9 GeV)
W_E	Hybrid wiggler	1.60	10.0	25	2.5	0.1-10000
W_F	Superconducting wiggler	5.0	14.	14	2	1-20000 (up to 40000 at 1.9 GeV)

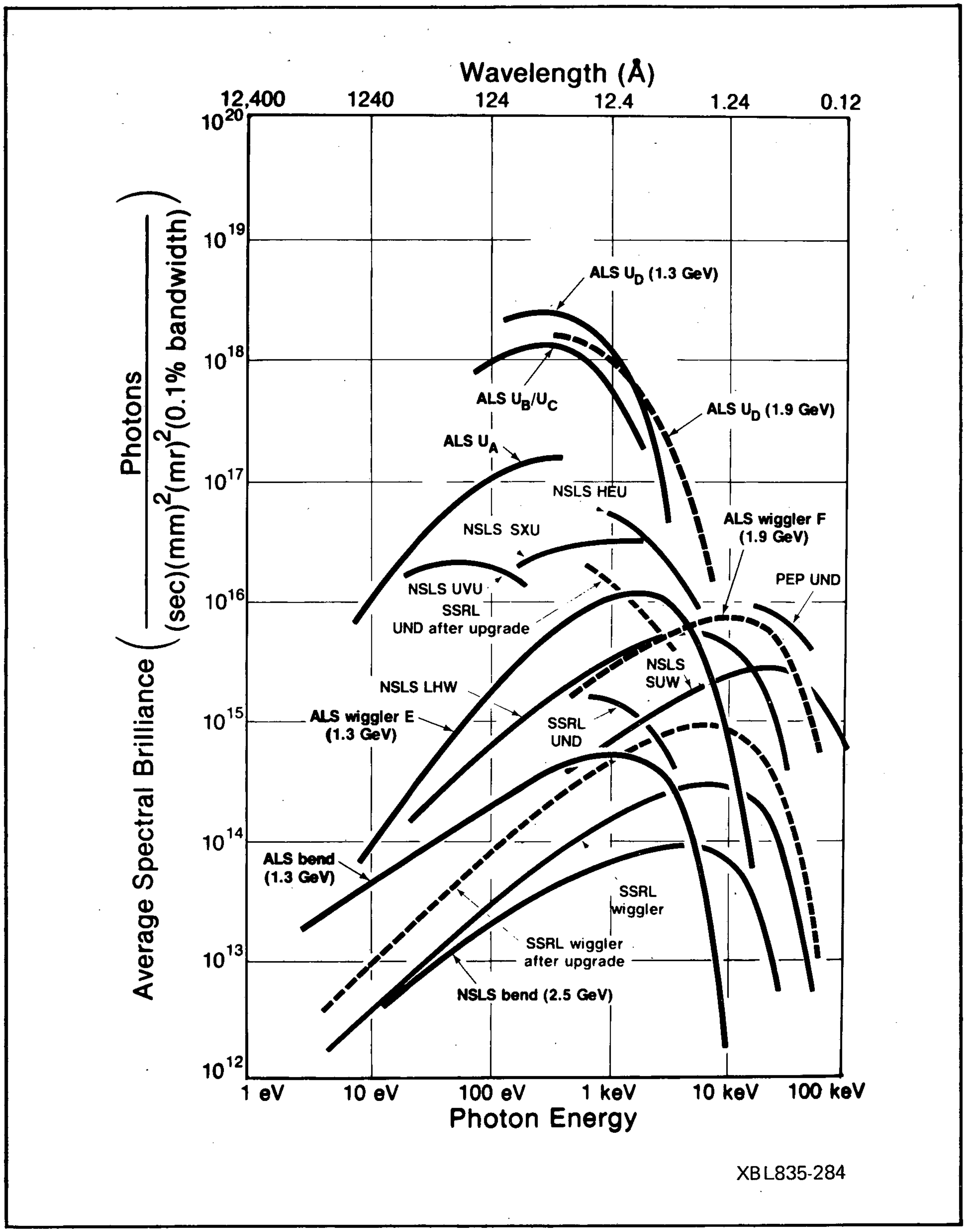


Figure A1-2. Spectral Brilliance Comparison of ALS Undulators, Wigglers, and Bending Magnets.

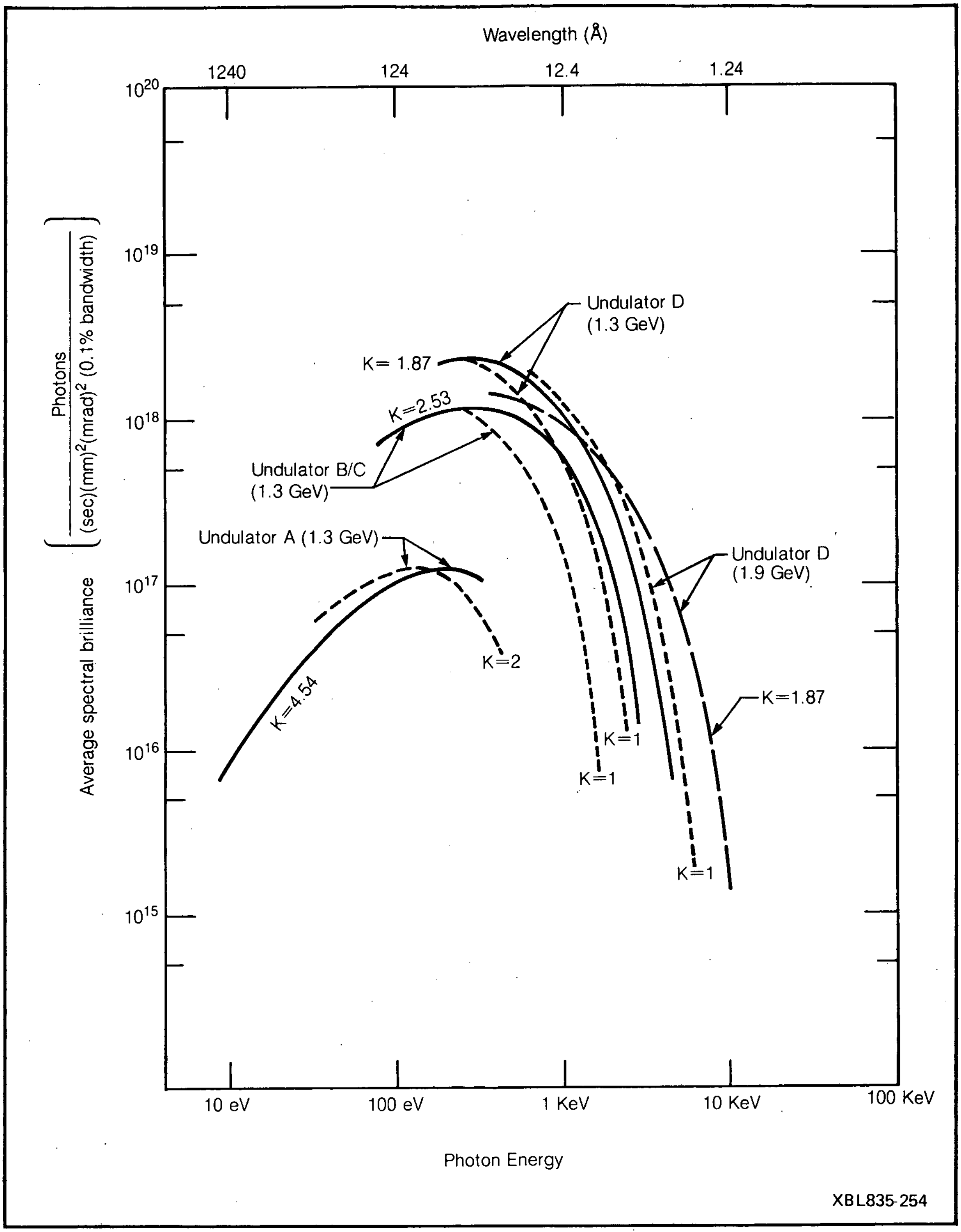


Figure A1-3. Spectral Brilliance from ALS Undulators.

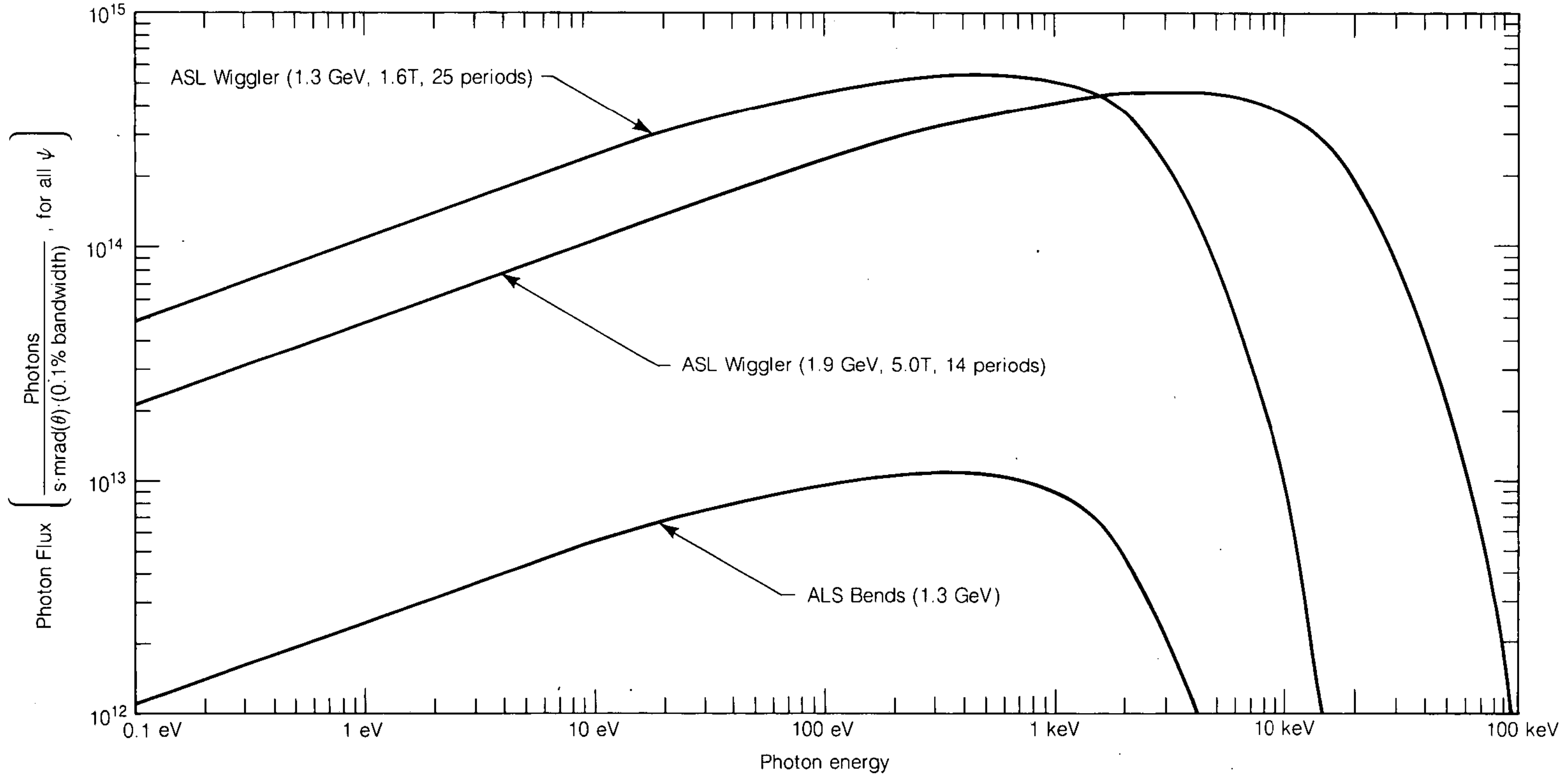


Figure A1-3a. Photon flux from wigglers compared with that from bend magnets at an electron current of 400 mA. A high-field wiggler can shift the spectrum to higher energies.

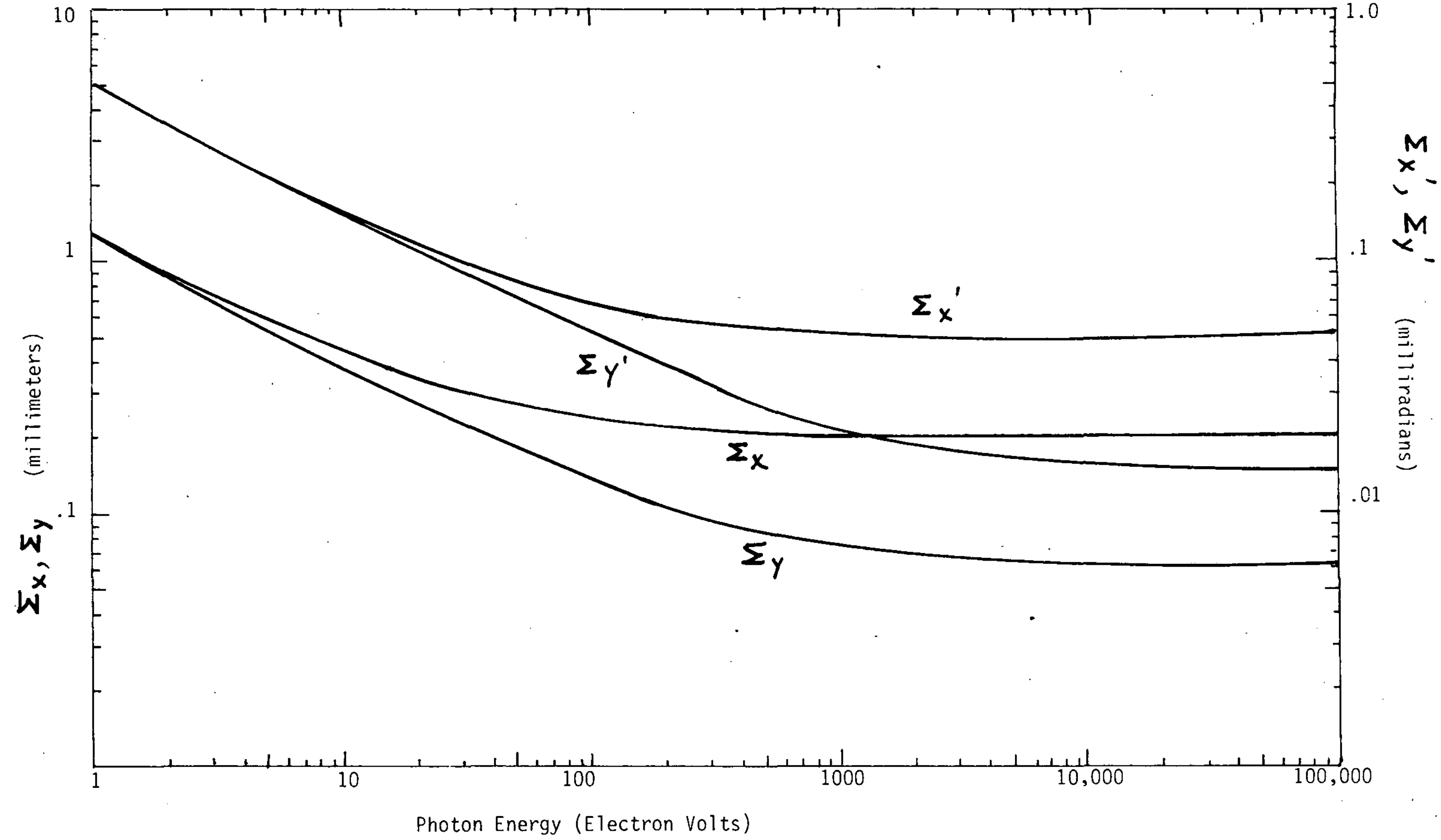


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Figure A1-4. ALS Undulators at 1.3 GeV. Angular Spread and Effective Source Size of the Central Peak of the Angular Distribution as a Function of Energy.

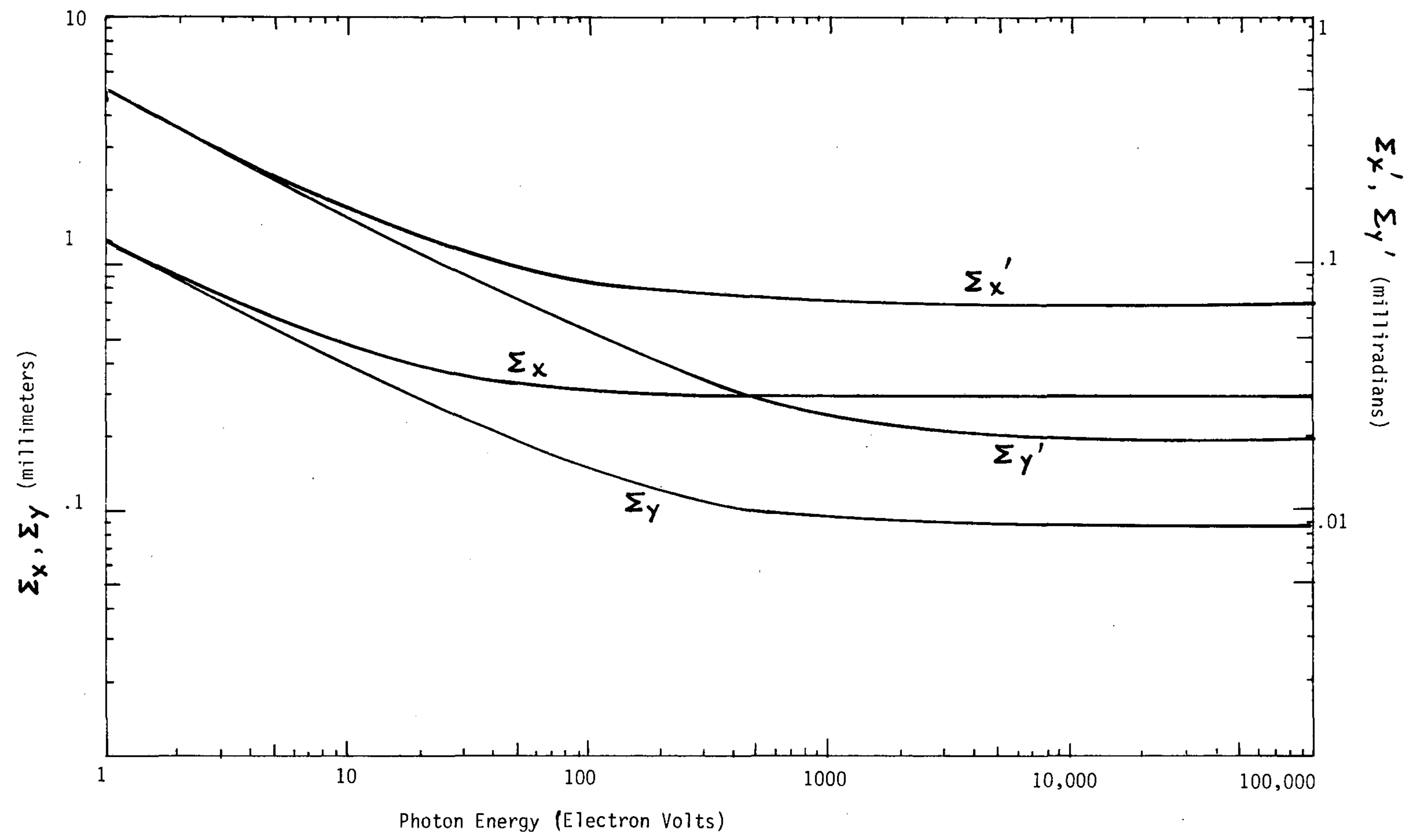

Figure A1-5. ALS Undulators at 1.9 GeV. Angular Spread and Effective Source Size of the Central Peak of the Angular Distribution as a Function of Energy.

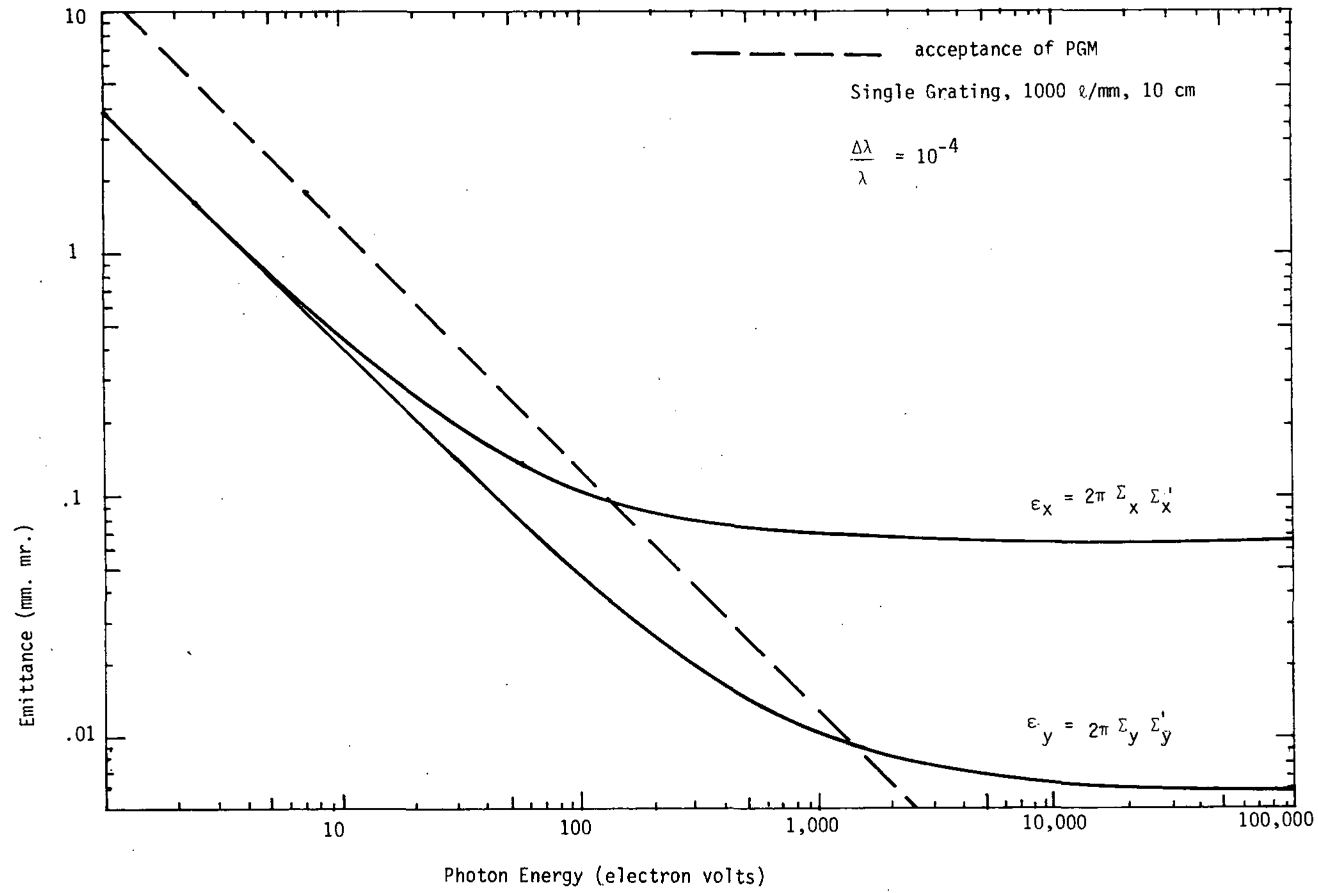

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Figure A1-6. Emittance of Undulator Sources (ALS 1.3 GeV) as a Function of Photon Energy. Also Shown is the Acceptance of a Plane Grating Monochromator (PGM) of Resolution $\Delta\lambda/\lambda = 10^{-4}$.

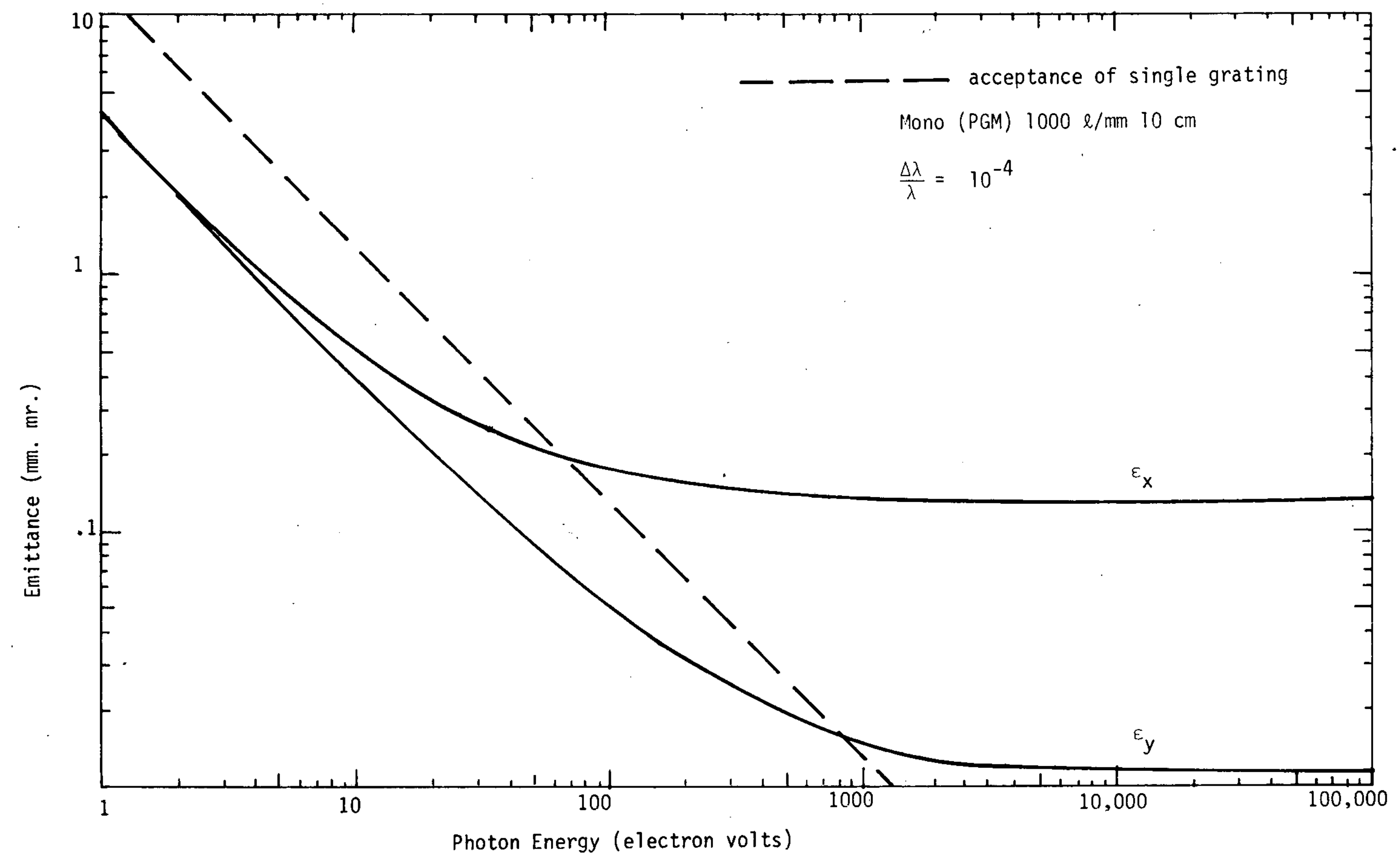

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Figure A1-7. Emittance of Undulator Sources (ALS 1.9 GeV). Also Shown is the Acceptance of a Plane Grating Monochromator (PGM) of Resolution $\Delta\lambda/\lambda = 10^{-4}$.

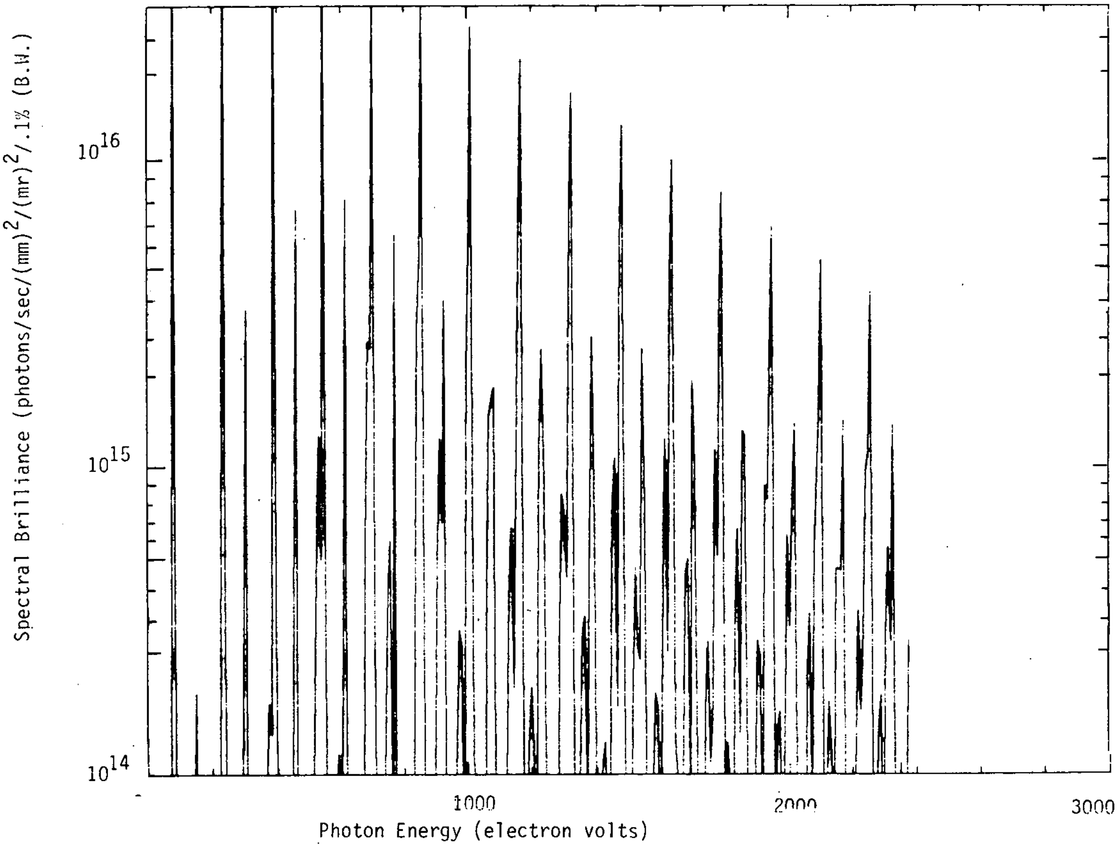

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Figure A1-8. Spectral Brilliance of Undulator B.

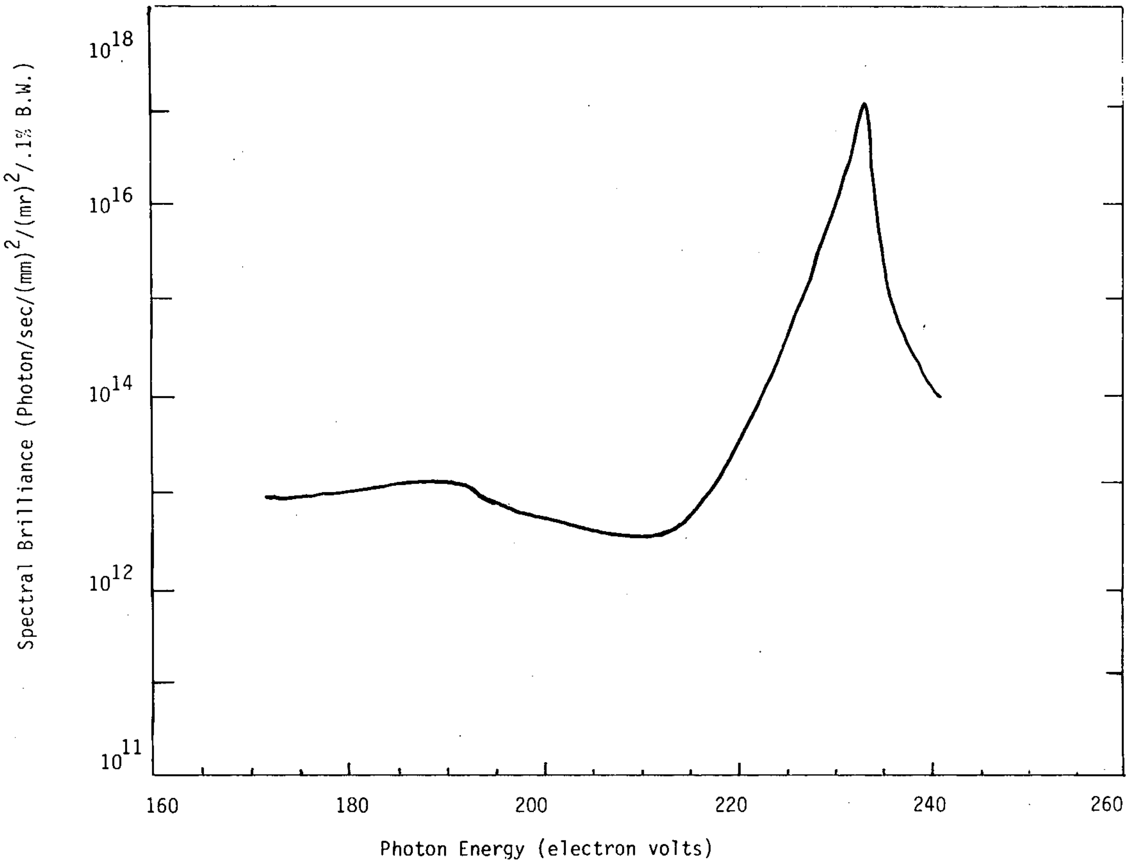

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Figure A1-9. Line Shape of the First Harmonic of Undulator B.

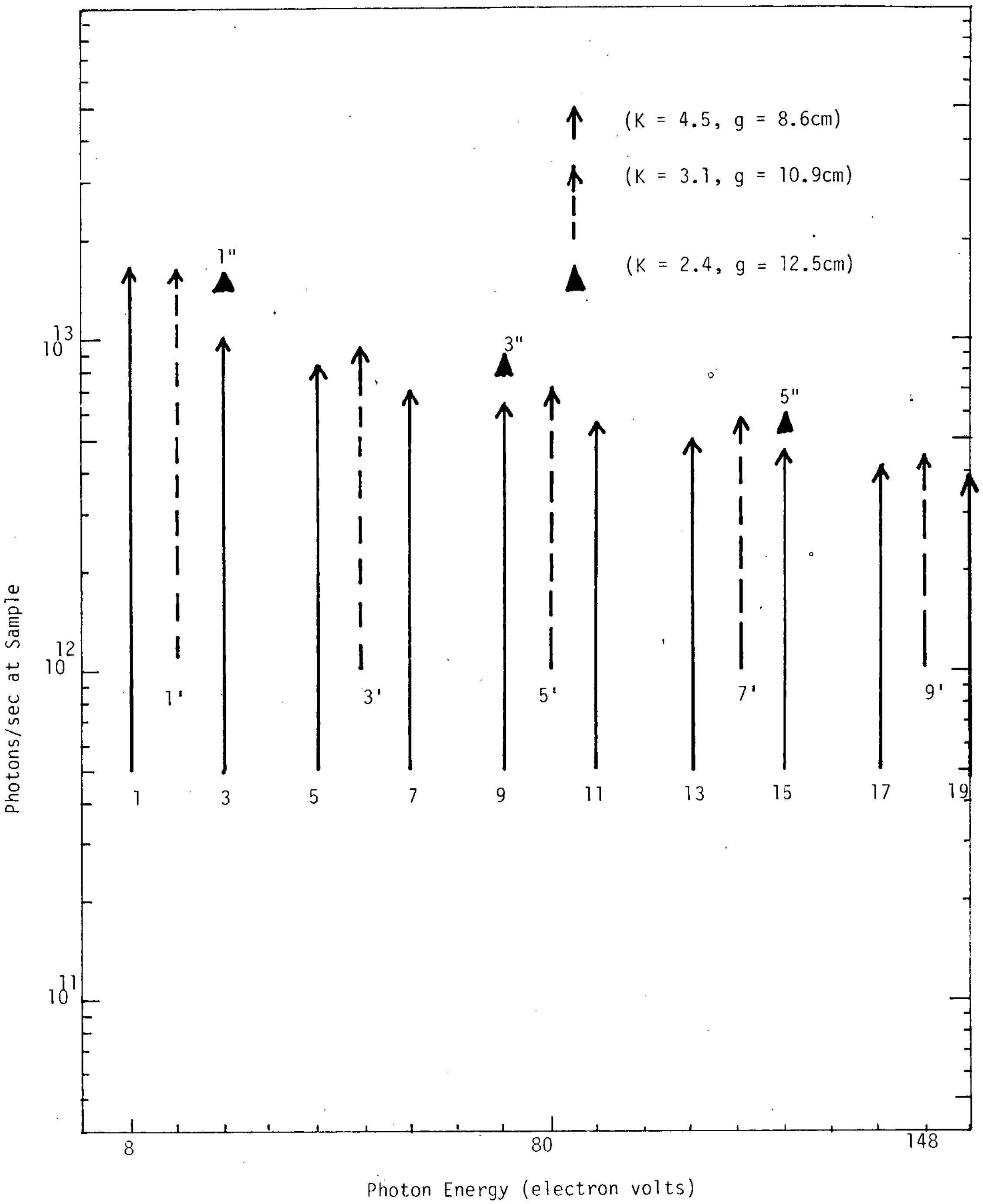

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Figure A1-10. Undulator A. Photons Collected* at Sample. The Energy Displacement of Harmonics is Shown for (3) Different Undulator Fields. *Assumptions: Overall Optical Efficiency (Mirror and Grating or Crystal) = 1.0%. Monochromator Bandwidth = 0.1%. The Monochromator Accepts 100% of the Central Angular Peak.

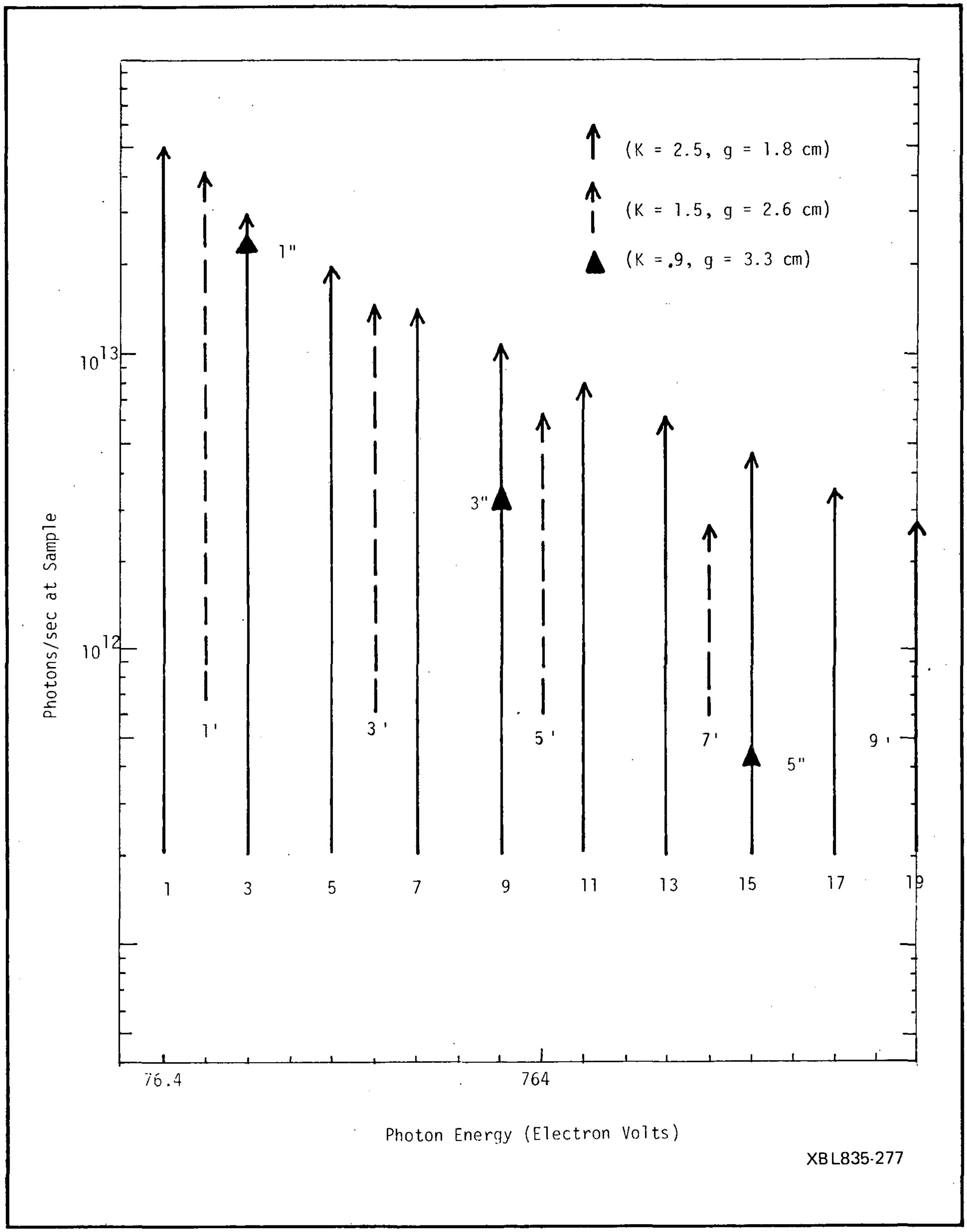

Figure A1-11. Undulators B,C. Photons Collected* at Sample. The Energy Displacement of Harmonics is Shown for (3) Different Undulator Fields. *Assumptions: Overall Optical Efficiency (Mirror and Grating or Crystal) = 1.0%. Monochromator Bandwidth = 0.1%. The Monochromator Accepts 100% of the Central Angular Peak.

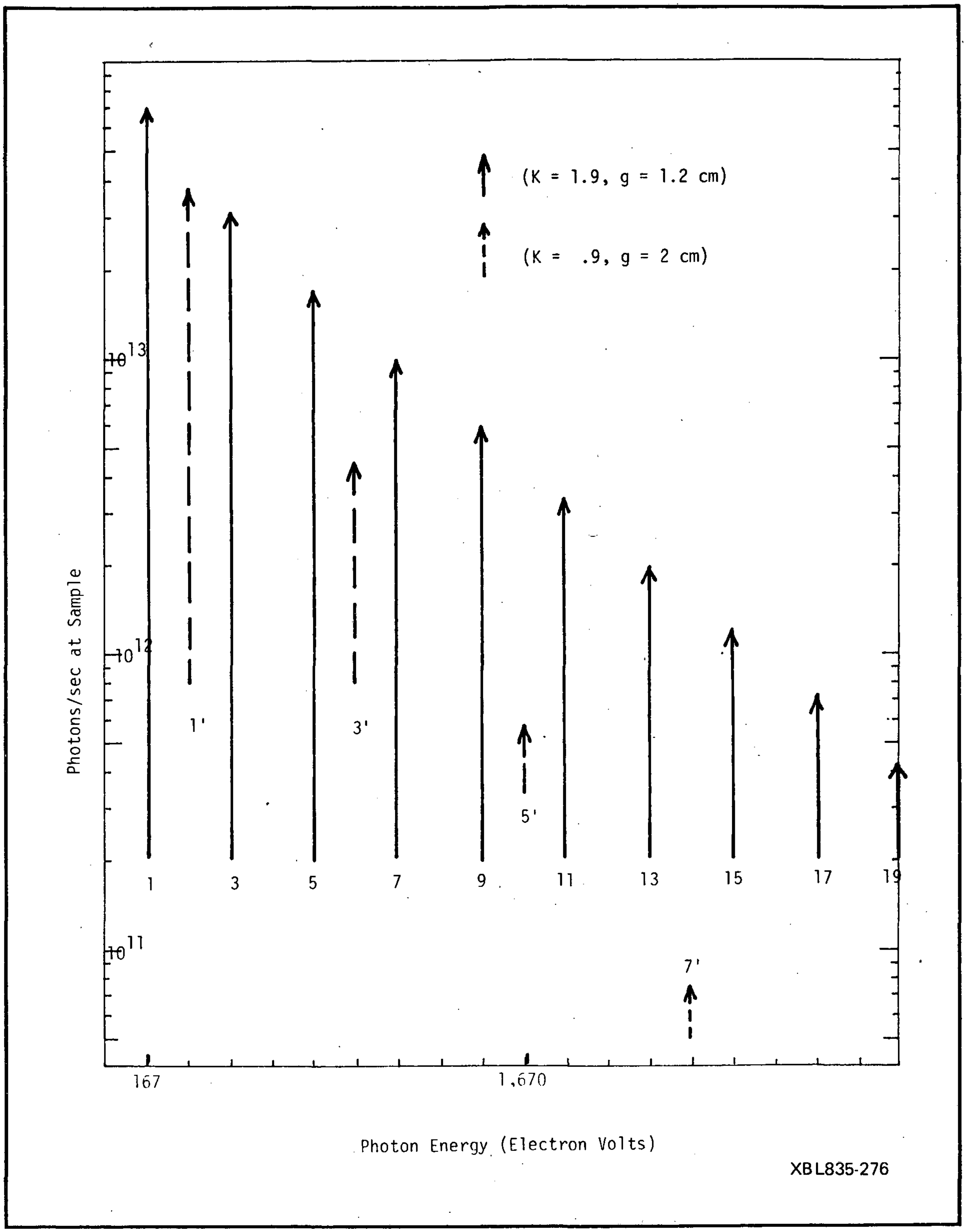

Figure A1-12. Undulator D. Photons Collected* at Sample. The Energy Displacement of Harmonics is Shown for (3) Different Undulator Fields. *Assumptions: Overall Optical Efficiency (Mirror and Grating or Crystal) = 1.0%. Monochromator Bandwidth = 0.1%. The Monochromator Accepts 100% of the Central Angular Peak.

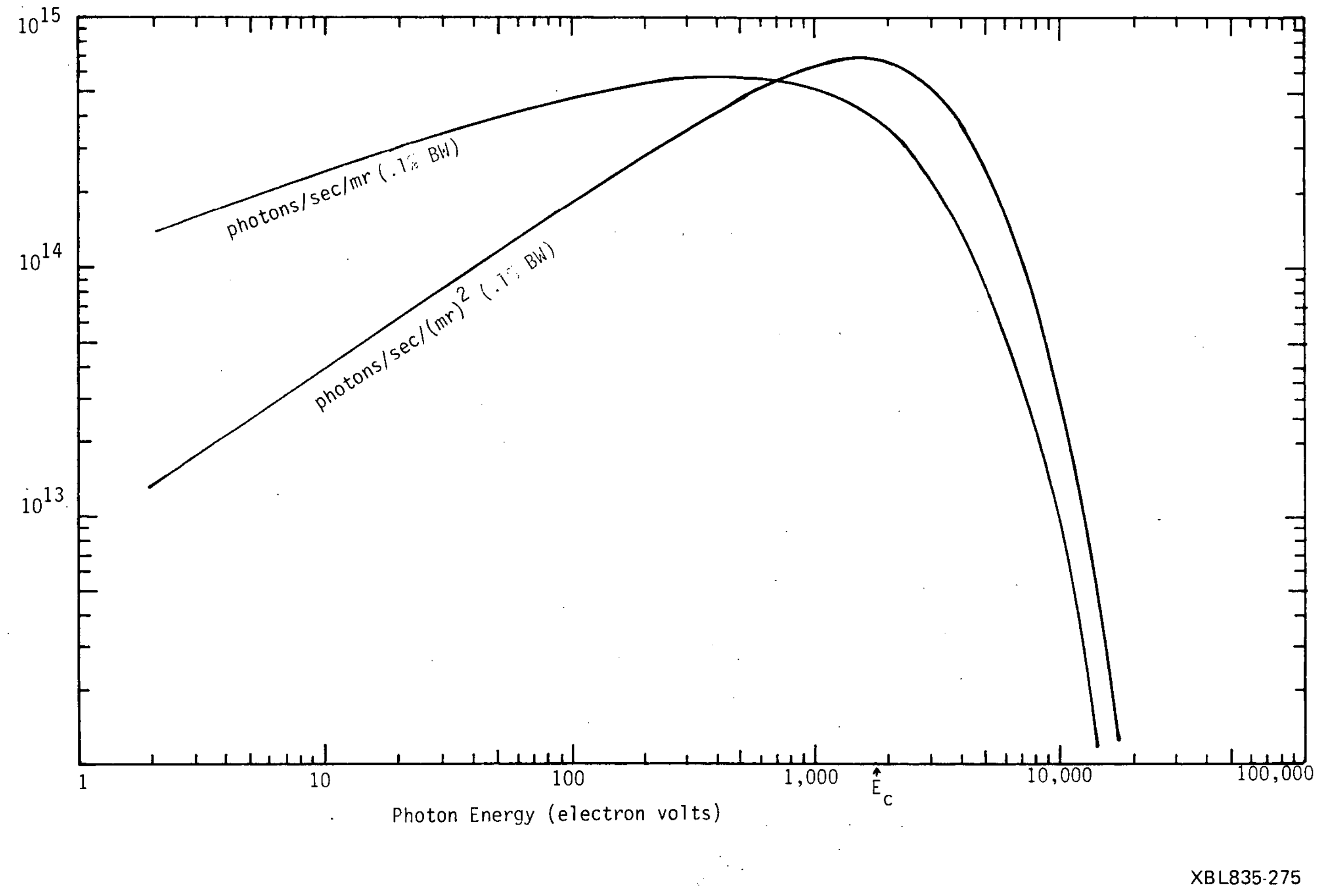

Figure A1-13. Wiggler E Spectrum (1.3 GeV).

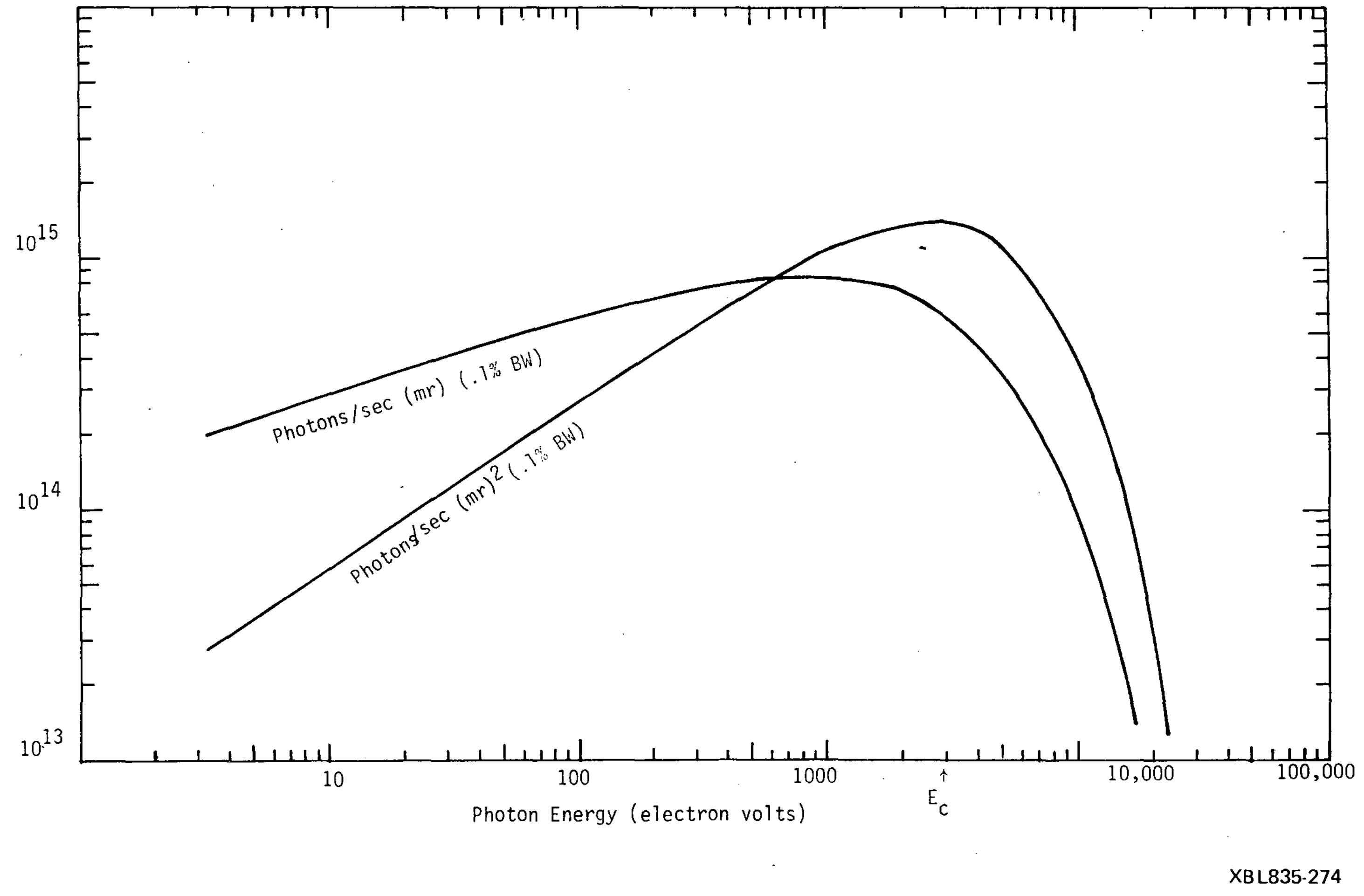

Figure A1-14. Wiggler E Spectrum (1.9 GeV).

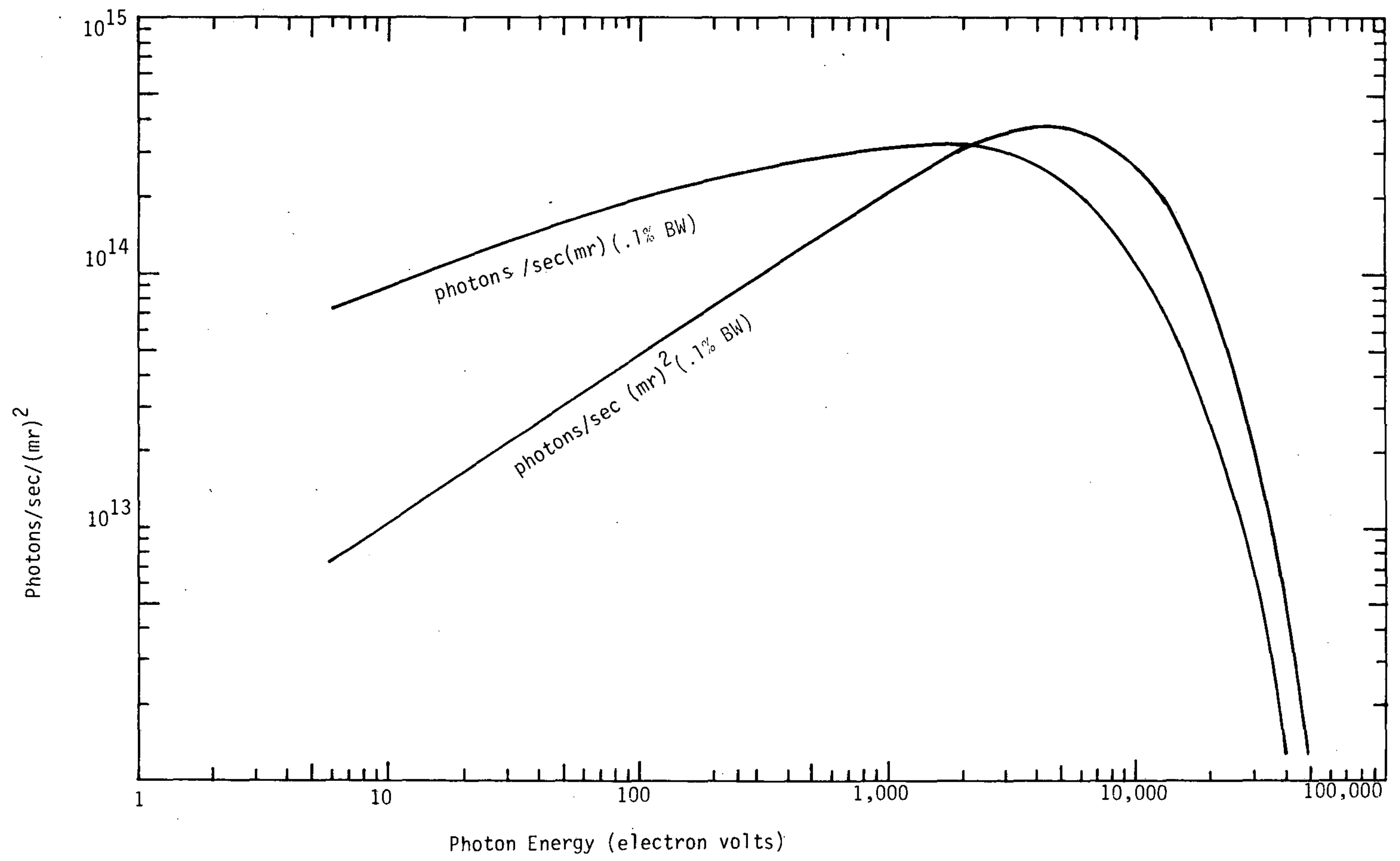

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Figure A1-15. Wiggler F Spectrum (1.3 GeV).

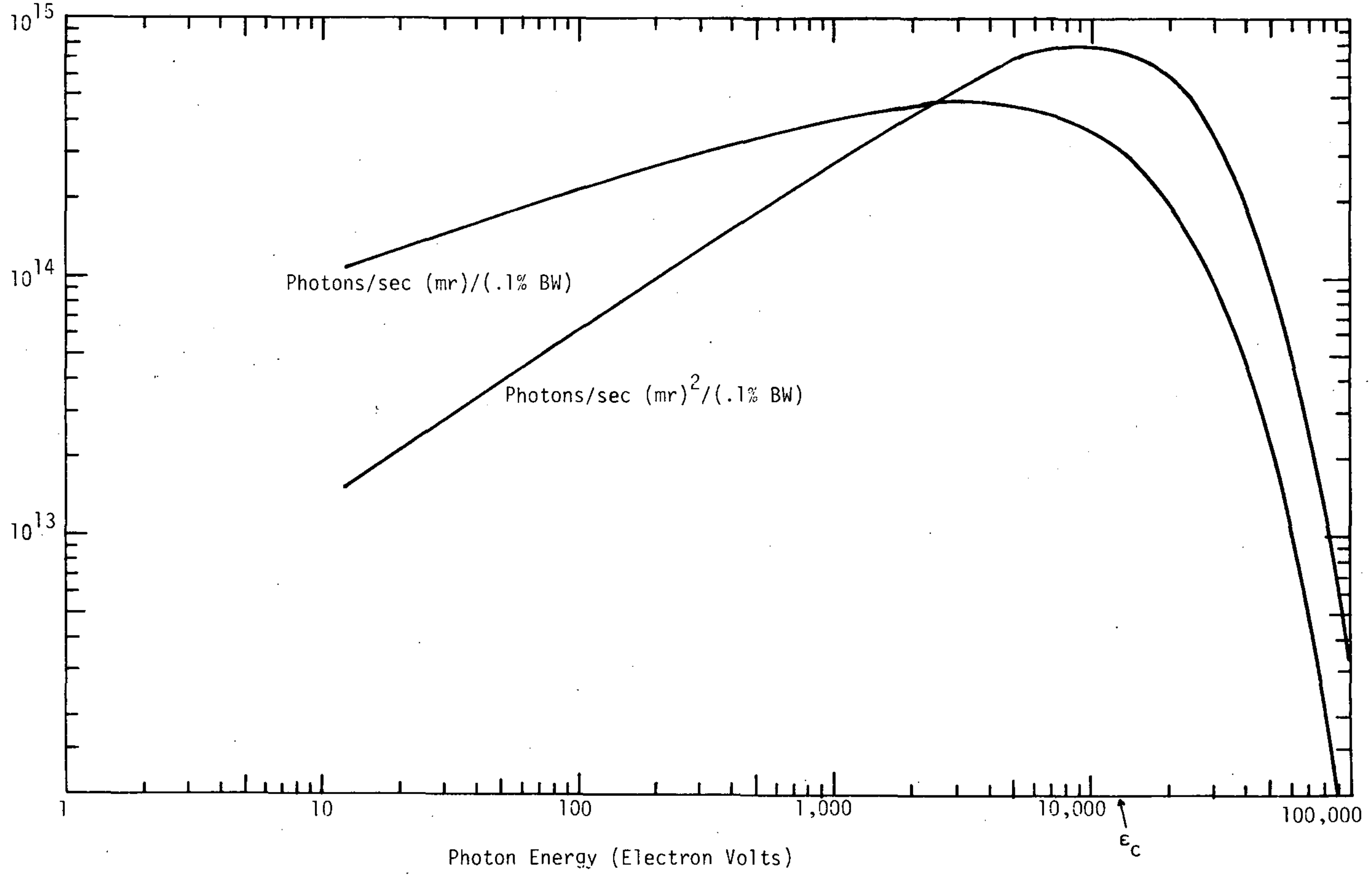

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Figure A1-16. Wiggler F Spectrum (1.9 GeV).

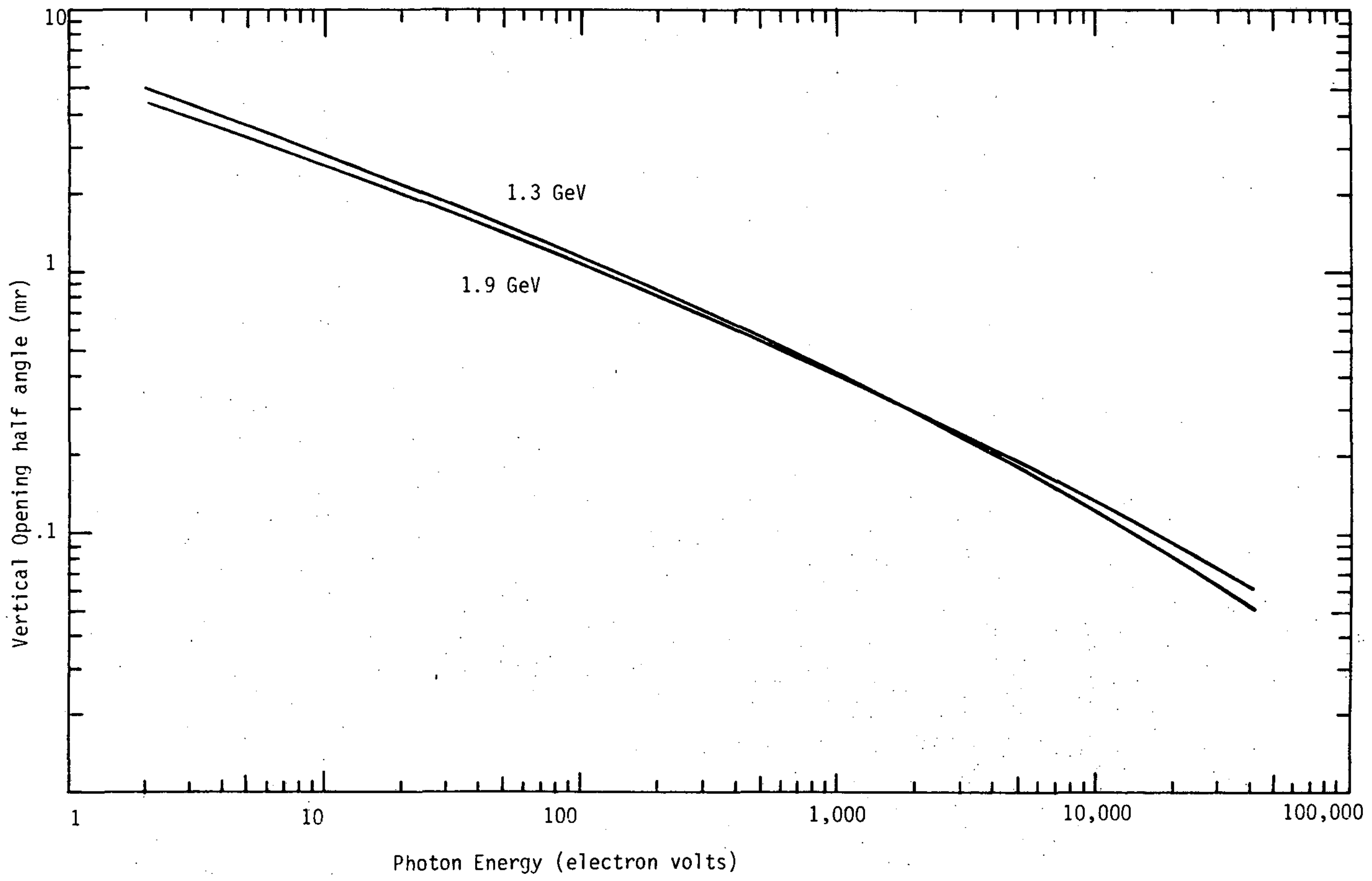

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Figure A1-17. Wiggler E - Vertical Opening Angle vs Energy.

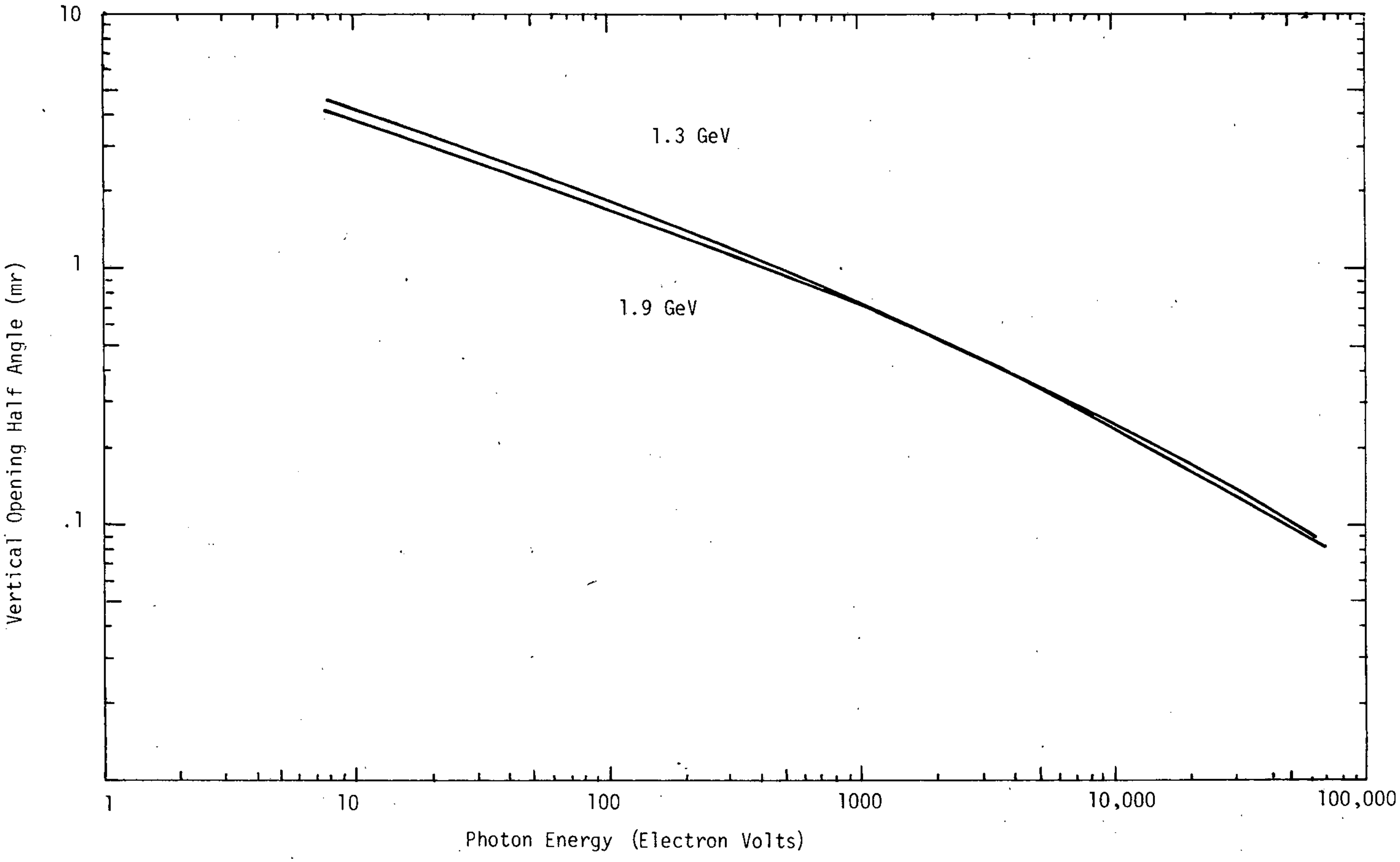

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Figure A1-18. Wiggler F - Vertical Opening Angle vs Energy.

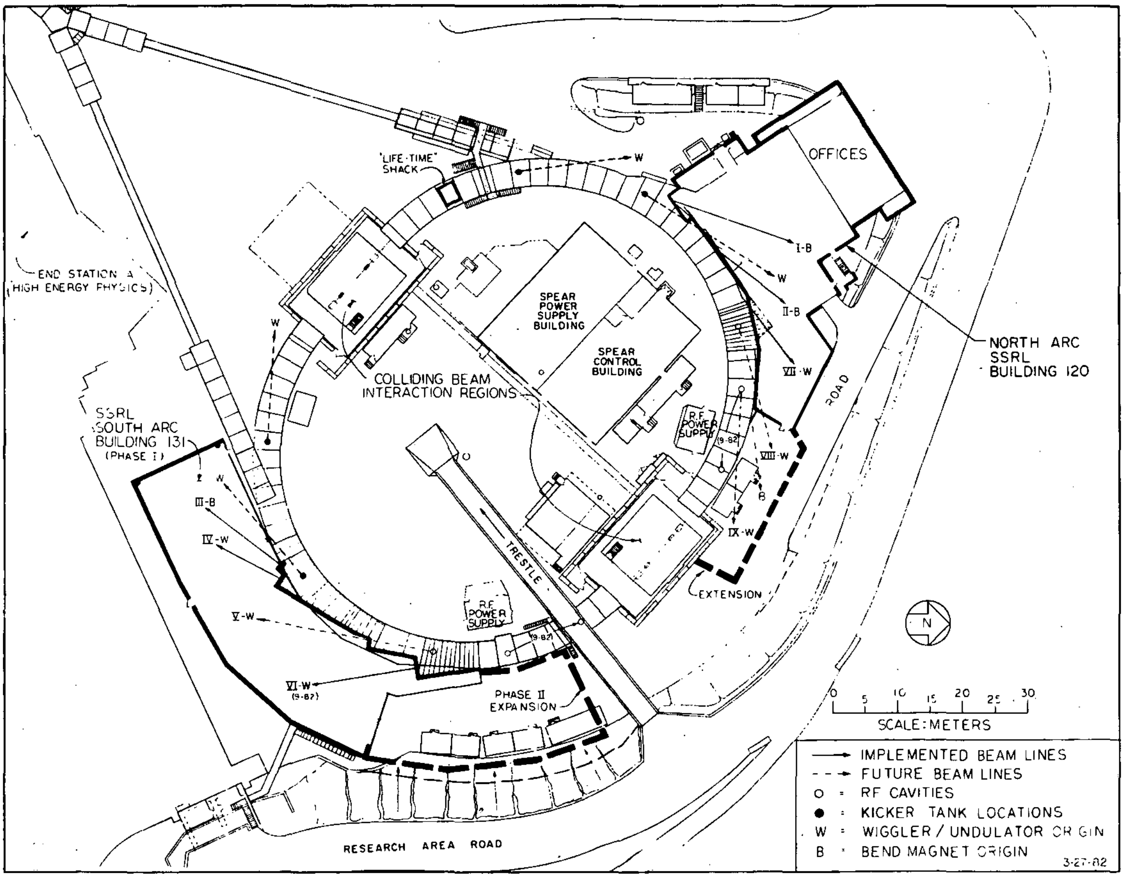
Identification	Angular Spread		Aperture		Ratio	E_1	Total Power	Avg. P. Den.	Avg. Power Transported
	H (mr)	V (mr)	H (mr)	V (mr)	APER./A.S.	(ev)	(Watts)	at 10 M (W/cm^2)	(within APER.)
SSRL									
Undulator	.26	.17	.18	.044	.18	660	72	416	13
PEP									
Undulator	.051	.17	.06	.02	.62	16,490	271	38,950	168
ALS									
UA (1.3)	1.79	.39	.18	.17	.1	8	182	65	18
UA (1.9)	1.22	.27	.13	.12	.1	18	388	296	39
UB (1.3)	1.00	.39	.076	.059	.011	76	629	402	7
UB (1.9)	.68	.27	.063	.042	.014	163	1,343	1,834	19
UD (1.3)	.74	.39	.063	.042	.009	167	696	603	6
UD (1.9)	.50	.27	.057	.03	.013	357	1,488	2,749	19
NSLS									
HEU	.29	.204	.24	.13	.55	1,000	993	4,245	546

Figure A1-19. Beam Power from Undulators.

Identification	Horiz. Avg. Spread, (mr)	E_c KeV	Total Power (Watts)	Avg. Power Density at 10M Incident W/CM^2	Avg. Beam Power Transported (Watts) (over Collection Angle mr)
SSRL Bend		4.7		26	89 (10 mr)
Wiggler IV	±12.9	10.8	3,325	379	645 (5 mr)
Wiggler VI	±1.45	7.78	1,821	1,846	1,821 (2.9 mr)
ALS					
W_E (1.3 GeV)	±5.9	1.80	2,741	297	1,165 (5 mr)
W_E (1.9 GeV)	±4.0	3.84	5,855	1,354	3,640 (5 mr)
W_F (1.3 GeV)	±25.7	5.60	20,980	519	2,040 (5 mr)
W_F (1.9 GeV)	±17.6	12.01	44,820	2,369	6,375 (5 mr)
NSLS					
LHW	±3.9	6.24	7,269	2,283	4,665 (5 mr)
SUW	±19.9	24.90	37,200	2,283	4,665 (5 mr)

Figure A1-20. Beam Power from Wigglers.

Appendix 2. Proposed Improvements to the Stanford Synchrotron Radiation Laboratory



Plan view of the SPEAR ring used by Stanford Synchrotron Radiation Laboratory. Planned construction is dashed.

The Stanford Synchrotron Radiation Laboratory (SSRL) is presently the world's preeminent hard x-ray synchrotron radiation facility and is among the best in the soft x-ray portion of the spectrum. The Stanford Synchrotron Radiation Laboratory utilities the 4-GeV storage ring, SPEAR, to produce synchrotron radiation at 15 experimental stations on five beam lines. Three of these beam lines are illuminated by bending magnets, while two can be illuminated by either 8-pole wigglers, constructed as a joint SSRL-SLAC project, or by a 30-period undulator, constructed as a joint SSRL-LBL project. Presently being designed and constructed are two new beam lines. One is an LBL-EXXON-SSRL collaboration, which will utilize a 54-pole wiggler constructed by LBL. Another is a Xerox-Stanford-SSRL collaboration, which will eventually utilize three undulators to provide high brightness in the 100- to 1000-eV range.

The SSRL-NCAM construction program has four goals

1) Decrease the emittance, leading to a major improvement in the photon flux and brightness available at SSRL in all spectral regions.
2) Increase the time available at SSRL for experimentation and increase its effectiveness.
3) Develop and test new insertion devices as well as the techniques for utilizing many insertion devices on one storage ring.
4) Gain additional experience in the commissioning of low emittance storage rings.

For two fundamental reasons, improvements to SSRL are an important part of NCAM. First, SSRL will provide synchrotron radiation for NCAM research during ALS construction. Even after the ALS is built, SSRL's hard x-ray capability will support NCAM research, because the ALS emphasizes the VUV and soft x-ray portions of the spectrum. Second, although the design of the ALS storage ring itself is complete, NCAM-sponsored research and development of insertion devices and beam lines at SSRL will provide information that can help in optimizing the ultimate utilization of ALS, while taking an important step toward the next-generation hard x-ray synchrotron source. Both the ALS and the next-generation hard x-ray machine will rely primarily on insertion devices for producing their beams. The SSRL improvements should generate experience and information about how several insertion devices affect beam quality and the operation of the storage ring.

The experience gained in implementing the planned improvements at SSRL and handling the intense, hard x-ray beam will be vital preparation for building what many synchrotron radiation users believe will be the machine of the future. Such a high-energy synchrotron radiation facility is currently beyond the state of the art in many respects. "Optical" elements and detectors for the photon beam lines are not available, and new approaches may be required to optimize the accelerator for hard x-ray photon generation. Although there is no question that such a machine would open up vast new areas of science, the knowledge and technology available today are not equal to the task of designing it.

To meet its goals, the SSRL-NCAM project includes both new construction and alterations to existing facilities. There are four major aspects to the project.

Construction of a 10,000-square-feet addition to Building 131 will bring the first floor and mezzanine almost all the way around to the SPEAR trestle. By shifting activities from existing space to this new space, room will be provided for new insertion-device beam lines. The addition will also provide the extra experimental setup and office space required to support research at the new beam lines.

Alteration of the storage ring SPEAR and its injection system should reduce the emittance by a substantial amount (up to a factor of about 4), bringing it almost to the planned emittance of the NSLS rings. As shown in Figure A2–1, this emittance reduction will increase the brightness of all SSRL beam lines by about an order of magnitude and will allow higher x-ray energies to be achieved with undulators. The performance of all the SSRL beam lines will also be improved through the reduction of beam bounce. In addition, increases in the total amount of time during which SPEAR can be dedicated to synchrotron-radiation production will be achieved through modifications to an electron gun and injection system proposed for addition to the SLAC linac by American University.

Two insertion devices producing ultra-high hard- and soft-x-ray brilliances and photon fluxes will be constructed and installed at SPEAR. The exact nature of these devices has not yet been determined, and advice from users is being solicited at workshops such as this one.

The last part of the proposed improvements is the construction of an ultra-high brilliance x-ray undulator beam line at PEP. This beam line will provide the most brilliant x-ray beam in the world in the 10- to 30-keV spectral region and will make possible new experiments that are otherwise impossible to perform.

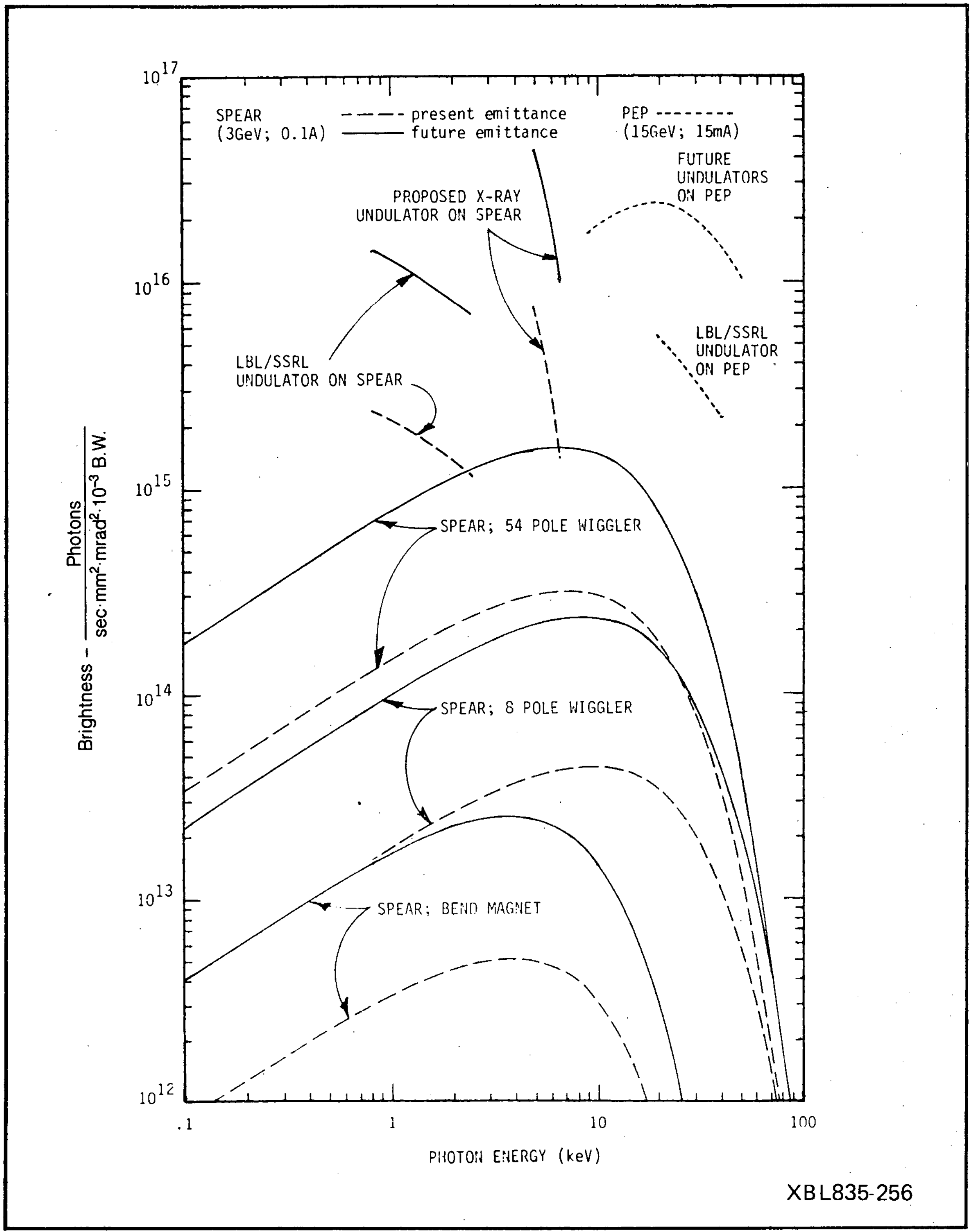


Figure A2-1. Increases in SSRL average spectral brilliance expected to occur as a result of the planned improvements.

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Appendix 4

AGENDA
ALS/SSRL USERS WORKSHOP

Lawrence Berkeley Laboratory
May 9-11, 1983

	Monday May 9		Tuesday May 10			Wednesday May 11
8:00 am	**REGISTRATION** **50 Auditorium**					
8:30 am	*Welcome and Charge to the Workshop* David A. Shirley, Director/LBL **50 Auditorium**		*Soft X-Ray* Joachim Stöhr EXXON Group Leader **50 Auditorium**			*Group Leaders continue preparation of drafts of group findings*
9:00 am	*Future of Synchrotron Radiation Research* Yves Petroff/LURE University of Paris **50 Auditorium**					*Discussion of drafts by each working group* (six parallel sessions)
10 am	*SSRL Upgrade* Arthur Bienenstock/SSRL **50 Auditorium**					
11 am	**LUNCH**		**LUNCH**			**LUNCH**
12:30 pm	*Advanced Light Source* Tom Elioff/LBL **50 Auditorium**		*High Brilliance Chemistry* Yuan T. Lee/LBL	*X-Ray Lithography Microscopy and Interference Effects* David Attwood LLNL	*Infrared* Paul Richards Univ. of Calif Berkeley	*Presentations of Group Findings* *• Hard X-Ray* *• Soft X-Ray* *• VUV* *• X-Ray Lithography, Microscopy and Interference Effects* *•High Brilliance Chemistry* *•Free Electron Laser*
1:30 pm	*Hard X-Ray* George Brown SSRL Group Leader **50 Auditorium**	*VUV* David Lynch Iowa State. U. Group Leader **70A**			*Free Electron Lasers* Andrew Sessler LBL	
2:00 pm						
2:30 pm			*Open*			
3:30 pm						**Break**
4:30 pm						*Concluding Talks* Arthur Bienenstock/SSRL Hermann Grunder/LBL
5:30 pm	*Wine and Cheese Reception* **LBL Cafeteria**		*Group Leaders and Writers produce draft of Group Findings*			**Open**
7:00 pm	**Open**		**Open**			