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an ALS *handbook*

*A Summary of the Capabilities and
Characteristics of the
Advanced Light Source*

April 1989

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Lawrence Berkeley Laboratory
University of California

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LBL-PUB--643-Rev. 2

DE89 011817

an ALS handbook

April 1989

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

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

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Preface

This booklet aims to provide the prospective user of the Advanced Light Source with a concise description of the radiation a researcher might expect at his or her experimental station. The focus is therefore on the characteristics of the light that emerges from insertion devices and bending magnets and on how components of the beam lines further alter the properties of the radiation. The few specifications and operating parameters of the ALS storage ring that are of interest are those that directly determine the radiation characteristics.

Sections 4 through 5 are primarily devoted to summary presentations, by means of performance plots and tabular compilations, of radiation characteristics at the ALS—spectral brightness, flux, coherent power, resolution, etc.—assuming a representative set of three undulators and one wiggler and a corresponding set of four beam lines. As a complement to these performance summaries, Section 1 is a general introductory discussion of synchrotron radiation and the ALS, and Section 2 discusses the properties of the stored electron beam that affect the radiation. Section 3 then provides an introduction to the characteristics of synchrotron radiation from bending magnets, wigglers, and undulators. In addition, Section 5 briefly introduces the theory of diffraction-grating and crystal monochromators.

As compared with previous editions of this booklet, the performance plots and tabular compilations of the ALS radiation characteristics are now based on conservative engineering designs rather than preliminary physics designs. Although expected to be more realistic, the performance specifications remain model-derived and should not be considered guaranteed.

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1. Introduction

For more than two decades, lasers have dominated the visible and infrared regions of the electromagnetic spectrum. During this same period, the most powerful sources of x-ray and ultraviolet radiation (collectively, the XUV) have been synchrotron light sources, where electrons circulating in an accelerator at relativistic velocities emit light as a by-product of their motion. In this category, the Advanced Light Source (ALS, Fig. 1-1) will offer researchers radiation of unprecedented brightness at XUV photon energies. With it, biologists can hope to watch processes unfold in living cells, chemists will be able to study chemical reactivity at a new level of precision, and materials scientists will address questions that can lead to new generations of semiconductor devices. Indeed, because specially designed "third-generation" synchrotron light sources such as the ALS are unique in producing such light, there are plans around the world to build several similar facilities. In the U.S., for example, the Advanced Photon Source, a facility complementary to the ALS for generating intense x-rays at still higher photon energies in the hard x-ray region of the spectrum, has been proposed for construction at the Argonne National Laboratory.

A special quality of the light produced by the ALS is its high spectral *brightness*, a composite measure of several virtues: the intensity of the light, the narrowness of its spectral distribution ($\Delta\lambda$), and the ease with which it can be focused to a small spot. Two special and interrelated features of the ALS make this high brightness possible. The first is the tightly constrained electron beam in the ALS storage ring. On the average, the electrons in any accelerator beam circulate smoothly around the ring. But, within the beam, individual electrons move around like the molecules in a gas, giving the beam a finite cross-sectional area. Since the electron beam is the source of the radiation, the beam cross section corresponds to the area of the source. Moreover, the random transverse motions of the electrons within the beam generate a spread in the solid angle into which the light is emitted. A parameter of the electron beam called the *emittance* measures the product of the beam size and divergence.

The storage ring sets limits on the quality of the synchrotron radiation, but it does not guarantee that they will be achieved. For this, the second feature of the ALS comes into play, namely, the extensive use of *undulators* in the long straight sections of the storage ring. It is the synchrotron radiation generated when the electrons pass through the undulators (undulator radiation) that has the highest brightness. Since the spectral purity ($\lambda/\Delta\lambda$) is proportional to the number of periods N in the undulator, long undulators with a large N

Fig. 1-1. Plan view of the Advanced Light Source, showing the exit ports for the envisioned set of approximately 60 beam lines. The ALS will be housed in an enlarged version of the domed hall that was the home of the historic 184-Inch Synchrocyclotron, as shown in the photo of an architectural model.

generate the highest-quality light. For example, the ALS undulator radiation will be centered in a narrow spectral line of width $\Delta\lambda$, with a spectral purity about equal to 100. With advanced monochromators, the spectral purity can be increased to as much as 30,000, but this improvement comes at the expense of photon flux.

Over a substantial portion of the spectral range of the ALS, which extends from photon energies of roughly 10 eV to 10 keV, a significant portion of the light from ALS undulators will also be spatially coherent, especially at photon energies below about 1 keV. *Spatial coherence* means that all waves across a light beam at any instant are in phase. The criterion for spatial coherence is that the product of the area of the light source and the solid angle into which it emits be no larger than the square of the wavelength of the light. Since this is the diffraction condition, spatially coherent light is said to be *diffraction limited*.

In accordance with the diffraction condition, the electron-beam emittance sets the minimum wavelength at which all the radiation can be diffraction limited. Even at wavelengths below the limit, part of the radiation remains diffraction limited, the fraction decreasing as the square of the wavelength. And the spatial coherence can be enhanced by the use of apertures, such as pinholes, that effectively reduce the source size, although this improvement comes at the expense of a reduced photon flux.

With spectral brightness comes the ability to focus the light to very small spots. Consider a Fresnel zone plate, which is a device to focus XUV radiation. It consists of a very large number of concentric rings of alternating x-ray-absorbing and -transmitting material, whose radial widths decrease from the center to the outer perimeter. Its focusing action on an incident plane wave can be visualized as that of a circular diffraction grating. The angle through which the wave is diffracted increases from the center (wide) rings to the outer (narrow) rings in such a way that each part of the diffracted wave meets at a focal spot whose radius is approximately the width of the outermost ring. If the incident radiation is not diffraction limited, light waves will be incident on the zone plate at significantly different angles and will be diffracted through a comparable range of angles, thereby increasing the size of the focal spot. If the radiation is not spectrally pure, the distance of the focal spot from the lens will be different for each wavelength, thereby enlarging the spot at any one distance.

Accordingly, spectral brightness brings with it the possibility of spatially resolved experiments of a wide variety, from imaging to combinations of microscopy with spectroscopy. Here it is the combination of a photon flux sufficient to elicit a measurable signal, focused onto an area small enough to provide the desired spatial resolution, that makes such experiments possible. For example, the ability to focus soft x-rays to a spot 75 nm in diameter was recently demonstrated at the National Synchrotron Light Source (NSLS) with zone plates having an outer zone width of 50 nm and the radiation from an undulator. Even without improvements in zone-plate technology, the spectral brightness of the ALS, which will be more than 100 times that available with existing facilities in this spectral range, will dramatically enhance the capabilities of x-ray microscopy, possibly including time-resolved imaging of dynamic processes, and of combined microscopy/spectroscopy such as elemental mapping by tuning the XUV photon energy to the absorption edges of important elements or spatially resolved photoemission spectroscopy. Moreover, by the time the ALS is operating, zone-plate technology will have advanced, perhaps providing x-ray lenses having a spatial resolution of several tens of nanometers.

Although undulators will provide the high-brightness XUV radiation that will be the ALS's major contribution to extending the frontiers of science, they will not be the only radiation sources. The ALS storage ring has 12 straight sections. One will be reserved for the injection of electrons into the storage ring from a booster synchrotron, and one will be partially occupied by radio-frequency cavities that feed energy into the electron beam. That leaves ten full and one partial straight section that will be available for a mix of undulators and wigglers, collectively called *insertion devices* (Fig. 1-2). A wiggler is optimized to generate an intense photon flux over a continuous, broad spectrum extending to the hard x-ray region, although it does this at the expense of spectral brightness.

At the normal 1.5-GeV operating energy of the ALS storage ring, the high-brightness undulators will cover the spectral range below about 2.0 keV. At the normal operating energy, wigglers will be able to reach to about 10 keV. The wigglers thereby extend the photon energy range of the ALS well beyond that available with the undulators, into the interesting spectral region where the *K* and *L* edges of many important elements lie. Wigglers will be useful sources of radiation for x-ray crystallography, surface x-ray absorption spectroscopy (SEXAFS), and microprobe spectroscopy.

Finally, the dipole magnets that bend the electron beam in the storage ring into its roughly circular trajectory will be sources of highly useful XUV radiation. Like wigglers, bending magnets generate a broad, continuous spectrum of light. The spectral brightness of the ALS bending-magnet radiation, although less than that from ALS wigglers, will compare

Fig. 1-2. Drawing of a generic insertion device for the straight sections of the ALS storage ring showing the main structural features that all undulators and wigglers will have in common.

very favorably with that from other synchrotron sources because of the low-emittance electron beam. At the ALS, 48 ports will be available for the extraction of radiation from bending magnets. The large number makes the use of bending-magnet radiation an attractive option for researchers needing long-term and regular access to XUV photons but not necessarily to photons of the highest spectral brightness. This is in contrast to the situation for insertion devices. Because of the small number of straight sections for insertion devices, the demand for them is likely to be high and access more limited.

LBL is strongly committed to operating the ALS as a national user facility open to all qualified scientists. The concrete expression of user-community needs will come with the formation of participating research teams whose members will devote both time and resources to the instrumentation of the ALS beam lines, including the experimental stations. Both insertion-device teams (IDTs) and bending-magnet teams (BMTs) are envisaged. In return for their effort and commitment of resources, members of the IDTs and BMTs will receive privileged access to the beam lines and experimental stations that they help develop. In keeping with our intent to operate a national user facility, however, a certain fraction of the beam time of every beam line will be made available to general users who are not members of these research teams. The fraction of time available to general users will usually range from 25% to 75%, depending on the type of beam line. In cooperation with the user community, a User Policy Statement that outlines the rights and responsibilities of all users has been written.

Based on the user requirements expressed in several topical workshops and in letters of interest received from prospective IDTs, conceptual design studies have begun on a complement of three undulators, one wiggler, and beam lines to carry the XUV radiation to experimental areas. Although this set of insertion devices covers the ALS spectral range and well illustrates the expected ALS performance, the final mix of undulators and wigglers and their precise performance characteristics will depend on the needs of the user community as expressed in IDT proposals. To aid in the evaluation of proposals, LBL has appointed a Program Review Panel consisting of nine non-LBL scientists respected for their research accomplishments in a broad range of fields.

2. Overview of the Storage Ring

2.1 Layout

The ALS is a third-generation synchrotron radiation source that is optimized for the use of insertion devices. An overall layout of the facility, which consists of a 50-MeV linac, a 1-Hz, 1.5-GeV booster synchrotron, and an electron storage ring optimized for 1.5 GeV, is shown in Fig. 2-1.

Performance characteristics of the ALS are determined primarily by the design of the storage-ring magnet *lattice*—the arrangement of bending and focusing magnets in the ring. For the ALS, we have chosen a lattice with 12 long straight sections joined by 12 achromatic arcs, each containing three bending magnets. This structure is called a triple-bend achromat (TBA). One of the 12 identical segments (superperiods) of the storage ring is shown in Fig. 2-2. Of the 12 straight sections in the storage ring, one is used for injection and one for the rf cavities; the remainder are available for insertion devices up to 5 m long. A summary of the major parameters of the storage ring is given in Table 2-1.

Synchrotron radiation beam lines will be available from the bending magnets, as well as from the insertion devices. The arrangement of possible photon beam ports is shown in Fig. 2-3. Up to four bending-magnet lines per superperiod may ultimately be available; however, the rightmost photon port will not be available in all arc sections.

2.2 Electron-Beam Size

Figure 2-4 shows a generic diagram of the electron-beam phase-space ellipse at some arbitrary location, s , along the storage-ring circumference. The rms beam emittance, defined in Eq. (2-1), represents the area in horizontal (x, x') or vertical (y, y') betatron phase space that encloses the beam:

$$\epsilon_x \equiv \gamma_x(s)x^2 + 2\alpha_x(s)xx' + \beta_x(s)x'^2 \quad (2-1)$$

$$\epsilon_y \equiv \gamma_y(s)y^2 + 2\alpha_y(s)yy' + \beta_y(s)y'^2$$

Fig. 2-1. Layout of the ALS accelerator complex showing the placement of the 50-MeV electron linear accelerator, the 1.5-GeV booster synchrotron, and the storage ring.

where α , β , γ are the Twiss parameters, characteristic of the lattice design. In fact, only two of the three parameters are required to specify the optics, since in each plane they are related at any location s by

$$\gamma(s) = \frac{1 + \alpha(s)^2}{\beta(s)} \quad (2-2)$$

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

Table 2-1. Main Parameters of ALS Storage Ring

Beam energy [GeV]	
Nominal	1.5
Minimum	1.0
Maximum	1.9
Circumference [m]	196.8
Beam current [mA]	
Multibunch	400
Single bunch	7.6
Beam emittance, rms [nm·rad]	
Horizontal	10
Vertical	1
Relative rms momentum spread	
Multibunch	8.0×10^{-4}
Single bunch	13.0×10^{-4}
Nominal bunch duration, FWHM [ps]	30-50
Radiation loss per turn [keV]	92
Length available for insertion devices [m]	5

A plot of the horizontal and vertical beta functions for one superperiod of the ALS lattice is shown in Fig. 2-5. The α parameter is simply related to the slope of the beta function in Fig. 2-5; that is,

$$\alpha(s) = -\frac{1}{2} \frac{d\beta(s)}{ds} \quad (2-3)$$

Fig. 2-3. Arrangement of photon beam ports in one superperiod of the storage-ring lattice showing one insertion-device port and four bending-magnet ports. From the angular separation of the ports, one can estimate the space available for experimental facilities at the end of a beam line of a given length.

Fig. 2-4. A generic electron-beam phase-space ellipse represents the area in betatron phase space that encloses the beam. From the ellipses for horizontal and vertical motion, one can determine the rms beam size (σ_x and σ_y) and divergence ($\sigma_{x'}$ and $\sigma_{y'}$).

In terms of these Twiss parameters, we can represent the rms beam size (σ_x and σ_y) and angular spread ($\sigma_{x'}$ and $\sigma_{y'}$) as

$$\sigma_x = \sqrt{\epsilon_x \beta_x(s)} \quad \sigma_{x'} = \sqrt{\epsilon_x \gamma_x(s)} \quad (2-4)$$

$$\sigma_y = \sqrt{\epsilon_y \beta_y(s)} \quad \sigma_{y'} = \sqrt{\epsilon_y \gamma_y(s)}$$

Fig. 2-5 Horizontal and vertical beta functions and dispersion for one super-period of the storage-ring lattice. The boxes at the top of the figure represent the locations of the three types of magnets shown in more detail in Fig. 2-2.

For the case of insertion devices, both α_x and α_y are zero at the center of the straight sections; therefore, for this special case, the rms angular spreads are given by

$$\sigma_x = \sqrt{\frac{\epsilon_x}{\beta_x^*(s)}} \quad (2-5)$$

$$\sigma_y = \sqrt{\frac{\epsilon_y}{\beta_y^*(s)}} .$$

where the asterisks denote that the beta functions are taken at the center of the straight section.

In the arc sections, there is another effect that adds to the observed horizontal beam size and angular spread: the presence of *dispersion*. Dispersion, D_x , refers to the correlation between the position of a particle and its momentum deviation, δp , from the nominal momentum, p_0 :

$$\delta x(s) = D_x(s) \left(\frac{\delta p}{p_0} \right) \quad (2-6)$$

$$\delta x'(s) = D_x'(s) \left(\frac{\delta p}{p_0} \right)$$

Since the beam size and angular spread arising from the dispersion are uncorrelated with the values due to betatron motion, we add the two contributions in quadrature to give

$$\sigma_x(s) = \sqrt{\epsilon_x \beta_x(s) + \delta x(s)^2} \quad (2-7)$$

$$\sigma_x'(s) = \sqrt{\epsilon_x \gamma_x(s) + \delta x'(s)^2}$$

Estimated values for the rms momentum spread expected in both the single-bunch and multibunch cases are included in Table 2-1. Values for the Twiss parameters and dispersion functions at the symmetry point of the insertion straight section and at the source points of the bending-magnet beam lines are given in Table 2-2.

Table 2-2. Values of horizontal (x) and vertical (y) Twiss parameters and horizontal dispersion functions at photon source points of the ALS storage ring.

Angle*		α	β	γ	D_x	D_y
Insertion Device						
0.0	x	0.0000	11.2094	0.0892	0.0000	0.0000
	y	0.0000	4.2256	0.2366		
Bending Magnets						
6.3	x	- 0.1609	0.3940	2.6041	0.0301	0.1134
	y	6.4655	20.3387	2.1045		
12.6	x	0.3968	0.8545	1.3546	0.0944	- 0.0563
	y	- 0.1075	1.4575	0.6941		
17.4	x	- 0.3968	0.8545	1.3546	0.0944	0.0563
	y	0.1075	1.4575	0.6941		
22.6	x	0.4378	0.4501	2.6477	0.0418	- 0.1352
	y	- 7.7339	19.0012	3.2005		

*Angle refers to the direction of the radiation from the source point, as shown in Fig. 2-3.

2.3 Time Structure

The ALS produces electron beams that are "bunched." Thus, an observer looking into the vacuum chamber would see that the circulating electrons in the storage ring do not form a continuous stream of particles; rather the electrons come in discrete bunches separated by empty spaces, where no particles are present. This pattern is illustrated schematically in Fig. 2-6.

The separation between beam bunches is governed by the wavelength of the radio-frequency (rf) system used to replenish the electron beam energy lost due to synchrotron radiation. This correspondence to the rf wavelength arises because the particles must maintain a fixed phase relationship to the rf wave in order to gain the requisite amount of energy on each revolution in the storage ring. For the ALS, the rf system has a frequency of $f_{rf} = 500$ MHz. The separation between bunches is then

$$\Delta s = \frac{c}{f_{rf}} = \frac{3 \times 10^8}{5 \times 10^8} = 0.6 \text{ m}, \quad (2-8)$$

or $\Delta t = \Delta s / c = 2 \text{ ns}$. This spacing is also illustrated in Fig. 2-6.

Fig. 2-6. Schematic illustration of the electron bunch structure in the ALS storage ring during multibunch operation. As shown at the upper right, each bunch has a full width at half maximum of about 35 ps. The spacing between bunches, dictated by the rf frequency, is 2 ns. (The electron pulse length is thus 1.75% of the bunch-to-bunch interval. If rendered to scale, the illustration at the left would show 250 narrow spikes, distributed around 80% of the ring's circumference.)

The maximum number of beam bunches that can be placed in a storage ring is equal to the total number of rf wavelengths that can fit around the circumference. For the ALS storage ring circumference of 196.8 m, $h = 196.8/0.6 = 328$. When all or almost all of these available rf "buckets" are filled, we call this the *multibunch* operating mode. However, to avoid trapping positive ions in the potential well of the negatively charged electron beam, it is necessary to leave a gap in the bunch train, as shown in Fig. 2-6. Therefore, in practice, we specify the ALS multibunch mode as having 250 contiguous bunches, followed by a gap of 78 empty buckets. For particular experiments, however—for example, those having to do with time-of-flight measurements—it can be advantageous to have only one circulating electron bunch in the storage ring; this is called the *single-bunch* mode. In this case, the repetition time of the single bunch is equal to the revolution time in the storage ring, i.e., 656 ns.

The intensity profile of each beam bunch is Gaussian, and its length can therefore be characterized in terms of its rms dimension, σ_r or σ_z . Here we represent the bunch length either in normal length units (e.g., meters) by the subscript r , or in time units (e.g., seconds) by the subscript z . For a beam bunch made up of particles having a velocity in the laboratory frame of βc , the two are simply related via the equation

$$\sigma_z = \frac{\sigma_r}{\beta c} \quad (2-9)$$

In addition to the rms bunch length, we often quote the value for the full-width-at-half-maximum (Γ_{FWHM}) bunch length, which is related to the rms length by $\Gamma_{FWHM} = 2.35 \sigma_r$ or $2.35 \sigma_z$.

The bunch length in a storage ring depends on (1) the parameters of the storage-ring lattice, (2) the rf system parameters, and (3) the impedance of the vacuum-chamber hardware. In the limit of low beam intensity, the first two of these determine a so-called natural, or zero-current, bunch length. For the ALS, this value is $\Gamma_{FWHM} = 24$ ps.

Beyond a threshold (peak) current, the bunches lengthen due to an instability (the longitudinal microwave instability). For the ALS, the amount of lengthening that occurs will depend on the vacuum-chamber impedance at very high frequencies. On the basis of experimental evidence from the SPEAR storage ring at Stanford, we expect the impedance seen by the beam to decrease markedly from its characteristic value at low frequencies. If this roll-off in the impedance at high frequencies (called "SPEAR scaling") is assumed, the bunch length for the ALS, in the multibunch mode, will increase with beam current, as indicated by the solid curve in Fig. 2-7. At the nominal current of 400 mA, the predicted bunch length is $2\sigma_z = 28$ ps.

If there were no decrease in the impedance at high frequencies, the beam bunches would be somewhat longer, as indicated by the dashed curve in Fig. 2-7. In this case, the nominal 400-mA bunch length would be $2\sigma_z \approx 60$ ps. Although the exact form of the impedance roll-off is likely to depend on the details of the actual storage-ring hardware, theoretical expectations indicate that some decrease will occur. Thus, we take the solid curve in Fig. 2-7 as a typical—but not exact—representation of what will be seen.

Fig. 2-7. Predicted electron pulse duration as a function of average circulating current, during multibunch operation. The best estimate (solid line) is based on a roll-off of vacuum-chamber impedance at high frequency, a phenomenon observed experimentally at SPEAR. The dashed line reflects the case of no impedance roll-off.

Similar bunch-length curves can be drawn for the single-bunch mode, as shown in Fig. 2-8. The previous discussion remains valid. In the single-bunch case, however, we envision more current in the bunch (7.6 mA in one bunch compared with 400 mA in 250 bunches, or 1.6 mA/bunch, for multibunch operation), so the bunch lengthening is somewhat greater.

Fig. 2-8. Predicted electron pulse duration as a function of average current, during single-bunch operation. The solid and dashed lines have the same meanings as in Fig. 2-7.

3. Characteristics of Synchrotron Radiation

3.1 Quantities Characterizing the Strength of the Radiation

3.1.1 Brightness and Flux. In discussing the propagation properties of radiation, the density of the photon flux in phase space plays a fundamental role and is generally referred to in optics as the brightness. A rigorous treatment of the phase-space concept in synchrotron radiation optics requires a generalization [Kim, 1985] of the textbook discussion of the radiation process in terms of the Wigner distribution function. Here we reserve the term *brightness* for the phase-space density of the photon flux, evaluated in the forward direction and at the center of the source, i.e., at the origin of the phase space, as follows:

$$\mathcal{B} = \frac{d^4 \mathcal{F}}{d\theta d\psi dx dy} \Big|_0 \quad (3-1)$$

Here θ and ψ are the horizontal and vertical angles, and x and y are the horizontal and vertical coordinates, respectively. (It should be noted that this quantity is sometimes called the brilliance.) The brightness uniquely characterizes the strength of a radiation source because it is invariant under propagation through linear optical elements, such as lenses or free space.

Integrating the phase-space density over the angles or the position coordinates, we obtain the spatial or angular density of flux:

$$\frac{d^2 \mathcal{F}}{dx dy} = \int \frac{d^4 \mathcal{F}}{d\theta d\psi dx dy} d\theta d\psi \quad (3-2)$$

$$\frac{d^2 \mathcal{F}}{d\theta d\psi} = \int \frac{d^4 \mathcal{F}}{d\theta d\psi dx dy} dx dy \quad (3-3)$$

For synchrotron radiation, the angular density of flux [Eq. (3-3)] has traditionally been the most familiar quantity, since it can be calculated from standard textbook formulas, and it is sometimes mistakenly called brightness. However, it is not an invariant measure of the source strength, because its magnitude depends on the nature of the beam-line focusing element. Finally, one obtains the flux by integration, as follows:

$$\bar{r} = \int \frac{d^2 \bar{r}}{d\theta d\psi} d\theta d\psi = \int \frac{d^2 \bar{r}}{dx dy} dx dy. \quad (3-4)$$

The flux is another invariant that characterizes the source strength.

It would clearly be convenient to consider the various differential fluxes introduced above in a small bandwidth around a given energy. In this case, we use the adjective *spectral*. Thus, we speak of the spectral brightness, spectral flux, the angular density of spectral flux, and so on.

3.1.2 Coherence. Another important characteristic of the photon beam is its coherence, which is a measure of the degree to which the radiation can exhibit interference patterns. Two types of coherence can be distinguished: The *transverse* (or spatial) *coherence* refers to the coherence of the electromagnetic disturbances at two points perpendicular to the propagation direction. The *longitudinal* (or temporal) *coherence* refers to the case of two points along the propagation direction.

Photons within the coherent phase-space area $\lambda/2$, where λ is the radiation wavelength, are transversely coherent. Since there are two transverse dimensions, the transversely coherent flux is given by

$$\bar{r}_{\text{coh},T} = A(\lambda/2)^2. \quad (3-5)$$

The temporal coherence is characterized by the coherence length l_c , which is related to the bandwidth $\Delta\lambda/\lambda$ by

$$l_c = \lambda/(\lambda/\Delta\lambda) = \lambda^2/\Delta\lambda. \quad (3-6)$$

3.1.3 Units. We choose the following units for the spectral flux and the brightness:

$$\bar{r} = \frac{\text{number of photons}}{(\text{s})(0.1\% \text{ bandwidth})}$$

$$\mathcal{B} = \frac{\text{number of photons}}{(\text{s})(\text{mm}^2)(\text{m}^2)(0.1\% \text{ bandwidth})}$$

The coherence will be characterized by the coherent power P_{coh} , which is defined to be the portion of the total power that is transversely coherent and that has a coherence length of

1 μm . With the above units, this becomes

$$P_{\text{coh}}/W = 7.63 \times 10^{-23} \times \hbar/\epsilon^2 [\text{keV}] \quad (3-7)$$

where ϵ is the photon energy.

3.2 Magnetic Structures

3.2.1 Bending Magnets. Electrons follow a circular trajectory in the bending magnets of storage rings. The radius of curvature ρ , in the extreme relativistic case, is given by

$$\rho = \frac{E}{e v B} \quad (3-8)$$

where E is the electron beam energy, v the velocity of light, and B the magnetic field strength. In practical units, this becomes

$$\rho(\text{m}) = 3.3 E [\text{GeV}] / B [\text{T}] \quad (3-9)$$

3.2.2 Wigglers and Undulators. Wigglers and undulators operate in the straight sections of storage rings and are collectively known as insertion devices. These are periodic magnetic structures in which the magnetic field B varies sinusoidally in the vertical direction:

$$B(z) = B_0 \cos(2\pi z / \lambda_u) \quad (3-10)$$

where z is the distance along the wiggler axis, B_0 the peak magnetic field, and λ_u the magnet period. Electron motion is also sinusoidal and lies in the horizontal plane. An important parameter characterizing the electron motion is the deflection parameter K , given by

$$K = e B_0 \lambda_u / 2\pi m c = 0.934 \lambda_u [\text{cm}] B_0 [\text{T}] \quad (3-11)$$

In terms of K , the maximum angular deflection of the orbit is $\delta = K/\gamma$. For $K \leq 1$, radiation from the various periods can exhibit strong interference phenomena, because the angular excursions of the electrons are within the nominal $1/\gamma$ radiation cone; in this case, the structure is referred to as an undulator. In the case $K \gg 1$, interference effects are less important, and the structure is referred to as a wiggler.

Short-period-length insertion devices producing high magnetic fields are usually constructed from permanent magnets. A typical insertion device, based on a permanent-magnet-steel hybrid design, is illustrated in Fig. 3-1. With optimum design, the peak field strength B_0 for neodymium-iron magnets is given by

$$B_0 = 3.44 \exp \left[-\frac{g}{\lambda_u} \left(5.08 - 1.54 \frac{g}{\lambda_u} \right) \right] ; 0.085 < \frac{g}{\lambda_u} < 0.8 \quad (3-12)$$

and for samarium-cobalt magnets by

$$B_0 = 3.33 \exp \left[-\frac{g}{\lambda_u} \left(5.47 - 1.8 \frac{g}{\lambda_u} \right) \right] \quad 0.07 < \frac{g}{\lambda_u} < 0.7 \quad (3-13)$$

where g is the full magnetic gap Halbach, 1983. These equations apply directly to wiggler designs, where the emphasis is on achieving a high peak field. For undulators, the deflection parameter K is more important, and the optimum magnetic design differs from that of a wiggler. Although there is no known universal function for the undulator field strength, a conservative engineering design results in peak fields approximately equal to 0.95 times the values derived from Eqs. (3-12 and 3-13).

Fig. 3-1. Schematic drawing of a periodic magnet structure (an undulator) of period λ_u and with a number of periods, N . The oscillations of the electron beam passing through the structure produce ultraviolet and soft x-ray radiation (photons) of high spectral brightness.

3.3 Optical Characteristics of Synchrotron Radiation

The radiation spectrum from a bending magnet is smooth, centered around the critical frequency ω_c . Wigglers can be regarded as a sequence of bending magnets of alternating polarity. Thus, a Wiggler's radiation characteristics are similar to those from bending magnets, apart from a $2N$ -fold enhancement of the intensity, where $2N$ is the number of the poles. (As a practical matter, the magnetic fields in a wiggler are usually much higher than those in a bending magnet; hence the radiation spectrum is typically pushed to higher energies.) In undulators, the interference of radiation from different parts of the trajectory

Fig. 3-1. Spectral flux as a function of energy for the four undulators and one wiggler described in Table 3-1, together with the bending magnets of the ALS. For the wiggler and bending magnets, we assume a 5-mr collection angle. For the undulators, the tuning range is shown for both the fundamental (solid lines) and the third harmonic (dashed lines).

Fig. 3-2. Spectral brightness of undulator U5.0 as a function of photon energy, in both the fundamental and the third harmonic. The sharp peaks illustrate the spectral profile of undulator radiation; the positions of the peaks can be tuned (dashed lines extending from 50 eV to 1.1 keV) by changing the undulator gap.

where

- $\bar{\nu}_B$ = photon flux (number of photons per second)
 θ = observation angle in the horizontal plane
 ψ = observation angle in the vertical plane
 α = fine-structure constant
 γ = electron energy/ $m_e c^2$ (m_e = electron mass, c = velocity of light)
 ω = angular frequency of photon ($\epsilon = \hbar \omega$ = energy of photon)
 i = beam current
 e = electron charge = 1.602×10^{-19} coulomb
 γ^* = $\omega/\omega_c = \epsilon/\epsilon_c$
 ω_c = critical frequency, defined as the frequency that divides the emitted power into equal halves, = $3\gamma^3 c/2\rho$
 ρ = radius of instantaneous curvature of the electron trajectory [in practical units, $\rho(\text{m}) = 3.3 E(\text{GeV})/B(\text{T})$]
 E = electron beam energy
 B = magnetic field strength
 $\epsilon_c = \hbar \omega_c$ in practical units, $\epsilon_c(\text{keV}) = 0.665 E^2(\text{GeV}) B(\text{T})$
 $X = \gamma\psi$
 $\xi = \gamma(1 + X^2)^{3/2}/2$

The subscripted K 's are modified Bessel functions of the second kind. In the horizontal direction ($\psi = 0$), Eq. (3-14) becomes

$$\frac{d^2 \bar{\nu}_B}{d\theta d\psi} \Big|_{\psi=0} = \frac{3\alpha}{4\pi^2} \gamma^2 \frac{\Delta\omega}{\omega} \frac{I}{e} H_2(\gamma), \quad (3-15)$$

where

$$H_2(\gamma) = \gamma^2 K_{2/3}^2(\gamma/2). \quad (3-16)$$

In practical units (photons $\cdot \text{s}^{-1} \cdot \text{mr}^{-2} \cdot (0.1\% \text{ bandwidth})^{-1}$),

$$\frac{d^2 \bar{\nu}_B}{d\theta d\psi} \Big|_{\psi=0} = 1.327 \times 10^{13} E^2(\text{GeV}) I(\text{A}) H_2(\gamma).$$

The function $H_2(\gamma)$ is shown in Fig 3-3.

The distribution integrated over ψ is given by

$$\frac{d \bar{\nu}_B}{d\theta} = \frac{\sqrt{3}}{2\pi} \alpha \gamma \frac{\Delta\omega}{\omega} \frac{I}{e} G_1(\gamma), \quad (3-17)$$

where

$$G_1(y) = y \int_y^\infty K_{5/3}(y') dy' . \quad (3-18)$$

In practical units [photons $\cdot$ s $^{-1}$ $\cdot$ mr $^{-1}$ $\cdot$ (0.1% bandwidth) $^{-1}$].

$$\frac{d\tau_B}{d\theta} = 2.457 \times 10^{13} E[\text{GeV}] I[A] G_1(y) .$$

The function $G_1(y)$ is also plotted in Fig 3-3.

Fig. 3-3. The functions $G_1(y)$ and $H_2(y)$, where y is the ratio of photon energy to critical photon energy.

Radiation from a bending magnet is linearly polarized when observed in the bending plane. Out of this plane, the polarization is elliptical and can be decomposed into its horizontal and vertical components. The first and second terms in the last bracket of Eq. (3-14) correspond, respectively, to the intensity of the horizontally and vertically polarized radiation. Figure 3-4 gives the normalized intensities of these two components, as functions of emission angle, for different energies. The square root of the ratio of these intensities is the ratio of the major and minor axes of the polarization ellipse. The sense of the electric field rotation reverses as the vertical observation angle changes from positive to negative.

Fig. 3-4. Normalized intensities of horizontal and vertical polarization components, as functions of the vertical observation angle ψ , for different photon energies. (Adapted from Green, 1977.)

Synchrotron radiation occurs in a narrow cone of nominal angular width $\sim 1/\gamma$. To provide a more-specific measure of this angular width, in terms of electron and photon energies, it is convenient to introduce the effective rms half-angle, σ_ψ , as follows:

$$\frac{d\mathcal{F}_B}{d\theta} \bigg/ \frac{d^2\mathcal{F}_B}{d\theta d\psi} \bigg|_{\psi=0} = \sqrt{2\pi} \sigma_\psi. \quad (3-19)$$

where σ_ψ is given by

$$\sigma_\psi = \frac{2}{\gamma\sqrt{2\pi}} C(\gamma) = 0.408 \frac{C(\gamma) |mr|}{E[\text{GeV}]}. \quad (3-20)$$

The function $C(\gamma)$ is plotted in Fig 3-5. In terms of σ_ψ , Eq. (3-15) may now be rewritten as

$$\frac{d^2\mathcal{F}_B}{d\theta d\psi} \bigg|_{\psi=0} = \frac{d\mathcal{F}_B}{d\theta} \frac{1}{\sigma_\psi \sqrt{2\pi}}. \quad (3-15a)$$

At the critical energy, σ_ψ becomes $0.65/\gamma$.

Strictly speaking, the above formula for the angular distribution is applicable only to the cases in which the effects of the electron beam divergences can be neglected. Such is, indeed, the case for the ALS.

To compute the brightness, we first evaluate the diffraction-limited source size

corresponding to the angle σ_ψ :

$$\sigma_r = \lambda / (4\pi\sigma_\psi). \quad (3-21)$$

To simplify the calculation, we neglect the effect of the curvature of the electron trajectory on the effective source size. The expression for the bending-magnet brightness then becomes

$$\mathcal{B} = \frac{d^2 \mathcal{F}}{d\theta d\psi} \bigg|_0 \left[\left(\sigma_x^2 + D^2 \sigma_e^2 + \sigma_r^2 \right) \left(\sigma_y^2 + \sigma_r^2 + \frac{\epsilon_y^2 + \gamma_y \sigma_r^2}{\sigma_\psi^2} \right) \right]^{1/2}. \quad (3-22)$$

In the above, γ_y is the third betatron function in the y direction, ϵ_y is the beam emittance, D is the dispersion function in the x direction, σ_e is the rms value of the relative energy spread, and $\sigma_x(\sigma_y)$ is the rms electron beam size in the $x(y)$ direction. Notice that the nonvanishing dispersion function in the bending magnet contributes to an additional term in the effective source size, proportional to the energy spread.

Fig. 3-5. The function $C(y)$. The limiting slopes, for $\epsilon/\epsilon_c \ll 1$ and $\epsilon/\epsilon_c \gg 1$, are indicated.

3.3.2 Wiggler Radiation. In a wiggler, K is large (typically $\gtrsim 10$) and radiation from different parts of the electron trajectory adds incoherently. The angular density of flux is then

given by $2N$ (where N is the number of magnet periods) times the appropriate formula for bending magnets, either Eq. (3-14) or Eq. (3-15). However, ρ or B must be taken at the point of the electron's trajectory tangent to the direction of observation. Thus, for a horizontal angle θ ,

$$\epsilon_c(\theta) = \epsilon_{c \max} \sqrt{1 - (\theta/\delta)^2} \quad (3-23)$$

where

$$\epsilon_{c \max} = 0.665 E^2 \text{GeV} B_0 T$$

When $\psi = 0$, the radiation is linearly polarized in the horizontal plane, as in the case of the bending magnet. As ψ increases, the direction of the polarization changes, but because the elliptical polarization from one half-period of the motion combines with the elliptical polarization (of opposite sense of rotation) from the next, the polarization remains linear. Calculation of the brightness for wiggler radiation must take into account the depth-of-field effects—the contribution to the apparent source size from different poles.

The brightness expression for wigglers is

$$\mathcal{E} = \frac{d^2 \mathcal{F}}{d\theta d\psi} \sum_{n=-\infty}^{\infty} \sum_{\pm} \frac{1}{2\pi} \frac{\exp \left[-\frac{1}{2} \left(\frac{X_0^2}{\sigma_x^2 + z_n^2 \sigma_v^2} \right) \right]}{\left[(\sigma_x^2 + z_n^2 \sigma_v^2) \left(\frac{\epsilon_v^2}{\sigma_v^2} + \sigma_x^2 + z_n^2 \sigma_v^2 \right) \right]^{1/2}} \quad (3-24)$$

$$z_{n\pm} = \lambda_n \left(n \pm \frac{1}{4} \right)$$

Here λ_n is the wiggler period. In the above, σ_x and σ_v (σ_x and σ_v) are the rms transverse size and angular divergence of the electron beam in the x direction (the v direction), respectively. The exponential factor in Eq. (3-24) arises because wigglers have two source points, separated by $2\lambda_0$, where

$$X_0 = \frac{K}{\gamma} \frac{\lambda_n}{2\pi} \quad (3-25)$$

The radiation pattern of a bending magnet or wiggler is illustrated in Fig. (3-6).

Fig. 3-6. Schematic illustration of the radiation pattern from wigglers and bending magnets. The spectrum is smooth, with a peak around the critical energy. For wigglers the depth-of-field effect gives the source size.

3.3.3 Undulator Radiation. When K is moderate (≤ 1), radiation from different periods interferes constructively, thus producing sharp peaks at harmonics of the fundamental ($n = 1$). Even when K is not small (≤ 10), sharp peaks are produced when effects of the electron-beam emittance can be neglected and if one considers lower harmonics.

Radiation characteristics of undulators depend sensitively on the electron-beam emittance. We consider first the case where effects due to emittance can be neglected. The wavelength of the fundamental on axis ($\theta = \psi = 0$) is given by

$$\lambda_1 = \frac{(1 + K^2/2)}{2\gamma^2} \lambda_u \quad (3-26)$$

or

$$\lambda_1 \text{ \AA} = \frac{13.056 \lambda_u [\text{cm}]}{E^2 [\text{GeV}]} (1 + K^2/2).$$

The corresponding energy, in practical units, is

$$E_1 \text{ keV} = 0.950 \frac{E^2 [\text{GeV}]}{(1 + K^2/2) \lambda_u [\text{cm}]}.$$

The relative bandwidth at the n th harmonic is

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta\omega}{\omega} \approx \frac{1}{nN} \quad (n = 1, 2, 3, \dots). \quad (3-27)$$

On axis the peak intensity of the n th harmonic is given by

$$\frac{d^2 \bar{r}_n}{d\theta d\psi} \bigg|_0 = \alpha N^2 \gamma^2 \frac{\Delta\omega}{\omega} \frac{I}{e} F_n(K) \quad (n = 1, 3, 5, \dots)$$

$$= 0 \quad (n = 2, 4, 6, \dots) \quad (3-28)$$

where

$$F_n(K) = \frac{K^2 n^2}{(1 + K^2/2)^2} \left\{ J_{\frac{n-1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] - J_{\frac{n+1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] \right\}^2 \quad (3-29)$$

Here, the J 's are Bessel functions. The function $F_n(K)$ is plotted in Fig 3-7. In practical units [photons $\cdot s^{-1} \cdot mr^{-2} \cdot (0.1\% \text{ bandwidth})^{-1}$], Eq. (3-28) becomes

$$\frac{d^2 \bar{z}_n}{d\theta d\psi} = 1.744 \times 10^{14} N^2 E^2 [\text{GeV}] f[A] F_n(K).$$

Fig. 3-7. The function $F_n(K)$ for various values of n , where K is the deflection parameter.

The angular distribution of the n th harmonic is concentrated in a narrow cone whose half-width is given by

$$\sigma_r \approx \sqrt{\frac{\lambda_n}{L}} = \frac{1}{\gamma} \sqrt{\frac{(1 + K^2/2)}{2Nn}} \quad (3-30)$$

Here L is the length of the undulator ($L = N\lambda_u$). Additional rings of radiation of the same frequency also appear at angular distances

$$\theta_{n,\ell} = \frac{1}{\gamma} \sqrt{\frac{\ell}{n} (1 + K^2/2)} \quad (\ell = 1, 2, 3, \dots). \quad (3-31)$$

The angular structure of undulator radiation is illustrated in Fig. 3-8 for the limiting case of zero beam emittance.

Fig. 3-8. The angular distribution of fundamental ($n = 1$) undulator radiation for the limiting case of zero beam emittance. The x and y axes correspond to the observation angles θ and ψ (in radians), respectively, and the z axis is the intensity in photons $\cdot$ s $^{-1}$ $\cdot$ amp $^{-1}$ $\cdot$ (0.1 mr) $^{-2}$ $\cdot$ (1% bandwidth) $^{-1}$. The undulator parameters for this theoretical calculation were $n = 14$, $K = 1.87$, $\lambda_u = 3.5$ cm, and $E = 1.3$ GeV. (Figure courtesy of R. Tatchyn, Stanford University.)

We are usually interested in the central cone. An approximate formula for the flux integrated over the central cone is

$$\mathcal{F}_n = \pi \alpha N \frac{\Delta\omega}{\omega} \frac{I}{e} Q_n(K), \quad (3-32)$$

or, in units of photons $\cdot$ s $^{-1}$ $\cdot$ (0.1% bandwidth) $^{-1}$,

$$\mathcal{F}_n = 1.431 \times 10^{14} N Q_n I [\text{A}].$$

The function $Q_n(K) = (1 + K^2/2)F_n/n$ is plotted in Fig. 3-9. Equation (3-28) can also be written as

$$\frac{d^2 \bar{f}_n}{d\theta d\psi} \bigg|_0 = \frac{\bar{f}_n}{2\pi\sigma_r^2} \quad (3-28a)$$

Fig. 3-9. The function $Q_n(K)$ for various values of n .

Away from the axis, there is also a change in wavelength: The factor $(1 + K^2/2)$ in Eq. (3-26) must be replaced by $[1 + K^2/2 + \gamma^2(\theta^2 + \psi^2)]$. Because of this wavelength shift with emission angle, the angle-integrated spectrum consists of peaks at λ_n superposed on a continuum. The peak-to-continuum ratio is large for $K \ll 1$, but the continuum increases with K , as one shifts from undulator to wiggler conditions.

The diffraction-limited source size (rms) corresponding to the angular divergence σ_r is

$$\sigma_r = \frac{1}{4\pi} \sqrt{\lambda L} \quad (3-33)$$

Electrons in storage rings are distributed in a finite area of transverse phase space position $\times$ angle. We reintroduce the rms beam sizes σ_x (horizontal) and σ_y (vertical) and beam divergences $\sigma_{x'}$ (horizontal) and $\sigma_{y'}$ (vertical). The quantities $\epsilon_x = \sigma_x \sigma_{x'}$ and

$\varepsilon_y = \sigma_y \sigma_{y'}$ are the horizontal and vertical emittances, respectively. Taking into account the electron-beam emittance, the rms transverse source size and the angular divergence in the x direction become, respectively,

$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_r^2}, \quad (3-34)$$

$$\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_r^2}, \quad (3-35)$$

and similarly for the y direction.

The angular density of flux becomes, instead of Eq. (3-28a),

$$\frac{d^2 \mathcal{F}_n}{d\theta d\psi} \bigg|_0 = \frac{\mathcal{F}_n}{2\pi \sigma_{Tx} \sigma_{Ty'}}. \quad (3-36)$$

For experiments that require a small angular divergence and a small irradiated area, the relevant figure of merit is the beam brightness $\mathcal{B}$. For an undulator, an approximate formula for the peak brightness is

$$\mathcal{B}_n(0,0) = \frac{\mathcal{F}_n}{(2\pi)^2 \sigma_{Tx} \sigma_{Ty'} \sigma_{Tx'} \sigma_{Ty'}}. \quad (3-37)$$

Figure 3-10 shows the spectral brightness for several synchrotron radiation sources. For undulators, each curve is the locus of sharp peaks that can be tuned by changing the undulator gaps.

The pattern of undulator radiation is illustrated in Fig. 3-11. That portion of the flux that is transversely coherent is given by

$$\mathcal{F}_c = \mathcal{B}_n \left(\frac{\lambda}{2} \right)^2 = \frac{\mathcal{F}_n \lambda^2}{(4\pi)^2 \sigma_{Tx} \sigma_{Ty'} \sigma_{Tx'} \sigma_{Ty'}}. \quad (3-38)$$

3.4 Power Loading

The power contained in the unwanted spectral regions should not be excessive, so as to limit thermal loading on the sensitive optical elements to tolerable levels. In this regard, the radiated power, integrated over all frequencies, is an important factor in beam-line design.

3.4.1 Power. The total power radiated by an undulator or wiggler is

$$P_T = \frac{N}{6} Z_0 I e \frac{2\pi c}{\lambda_u} \gamma^2 K^2, \quad (3-39)$$

Fig. 3-10. Average spectral brightness with a 0.1% bandwidth, as a function of photon energy, for a variety of synchrotron radiation sources. For each undulator, the brightness curve is the envelope of two or more harmonics.

where $Z_0 = 377$ ohms, or, in practical units,

$$P_T \text{ kW} = 0.633 E^2 \text{ GeV}^2 B_0^2 T L m I |A|.$$

Fig. 3-11. Schematic illustration of the radiation pattern from an undulator. The spectrum is sharply peaked around $\omega = n\omega_1$; the extent of transverse coherence depends on the ratio of the radiation phase-space area to the electron-beam phase-space area.

For bending magnets, B_0^2 in the above expression must be replaced by $2B^2$, where B is the magnetic field in the bending magnet. The angular distribution of the radiated power is

$$\frac{d^2P}{d\theta d\psi} = P_1 \frac{21\gamma^2}{16\pi K} G(K) f_K(\gamma\theta, \gamma\psi). \quad (3-40)$$

or, in units of $\text{W} \cdot \text{mr}^{-1}$,

$$\frac{d^2P}{d\theta d\psi} = 10.84 B_0^2 [T]^E^4 [\text{GeV}] I [A] N G(K) f_K(\gamma\theta, \gamma\psi).$$

The behavior of the angular function $f_K(\gamma\theta, \gamma\psi)$, which is normalized as $f_K(0,0) = 1$, is shown in Fig. 3-12. The function $G(K)$, shown in Fig. 3-13, quickly approaches unity as K increases from zero.

3.5 Special Undulators for Polarization Control

Planar undulators, in which all the pole faces are parallel, produce radiation with a high degree of linear polarization. Other kinds of polarized radiation can be obtained by using different magnet arrangements.

3.5.1 Helical Undulator. Helical undulators produce circularly polarized radiation. A permanent-magnet helical undulator consists of short segments of dipole magnets, each of

Fig. 3-12. The angular function f_K , for various values of the deflection parameter K : (a) as a function of the vertical observation angle ψ when the horizontal observation angle $\theta = 0$ and (b) as a function of θ when $\psi = 0$.

which is rotated by a fixed angle Θ relative to the previous one [Halbach, 1981]. Although such devices are rather complex, it should be possible to design a permanent-magnet helical undulator of variable Θ , hence of variable period. Such an undulator would be a promising source of circularly polarized radiation, tunable over a wide range of photon energies.

Fig. 3-13. The function $G(K)$.

3.5.2 Crossed Undulator. The sense of the polarization from the helical undulator described above cannot be reversed. For a variable-polarization capability, however, one can use a pair of planar undulators oriented at right angles to each other [Kim, 1984], as shown in Fig. 3-14. The amplitude of the radiation from these so-called crossed undulators is a linear superposition of two parts, one linearly polarized along the x direction and another linearly polarized along the y direction. By varying the relative phase of the two amplitudes by means of a variable-field magnet between the undulators, it is possible to modulate the polarization in an arbitrary way. The polarization can be linear and switched between two mutually perpendicular directions, or it can be switched between left circular

Fig. 3-14. Schematic drawing of a pair of crossed undulators that could be used to produce variably polarized radiation.

and right circular. For this device to work, it is necessary to use a monochromator with a sufficiently small bandpass, so that the wave trains from the two undulators are stretched and overlapped. Also, the angular divergence of the electron beam should be sufficiently small; otherwise, the fluctuation in the relative phase limits the achievable degree of polarization.

3.5.3 Other Devices. A planar undulator whose pole boundaries are tilted away from a right angle with respect to the axial direction can be used as a helical undulator if the electron trajectory lies a certain distance above or below the horizontal midplane of the undulator Halbach, 1985. Also, Onuki et al. [1988] have developed a variant of the crossed undulators in which the two orthogonal undulators overlap in the axial direction. Further study is required to evaluate the performance of this and other devices.

4. Representative Insertion Devices for the ALS

The ALS, operating at 1.5 GeV, is optimum for insertion-device operation in the vacuum-ultraviolet (VUV) and soft x-ray spectral regions. On a time-averaged basis, an ALS undulator will be the brightest source available in those photon energy ranges. In addition, for both lower and higher photon energies, undulators and wigglers (respectively) at the ALS will offer very useful capabilities.

Table 4-1 summarizes the parameters for three undulators and a wiggler, selected as a representative initial complement of ALS insertion devices. Figure 4-1 gives the spectral flux from these devices. This selection of insertion devices is based on user requirements enunciated at several topical workshops (see list of references) and in letters of interest received from prospective IDTs. Nonetheless, this selection is open to further adjustment as user needs are expressed in IDT proposals.

Figures 4-2 and 4-3 show the spectral brightness of the insertion devices of Table 4-1 and the ALS bending magnets. For undulators, each curve is the locus of sharp spectral peaks whose positions can be tuned by changing the magnet gaps. In general, there can be many prominent higher harmonics, especially for undulators operating at large K values. The details of the first, third, and fifth harmonics of the ALS undulators are shown in Fig. 4-3.

In comparison with previous editions of this handbook, the spectral-brightness curves reflect several changes. First is the use of the design value of the storage-ring rms horizontal emittance rather than the natural emittance, which lowers the spectral brightness. In addition, the momentum spread in the electron beam and imperfections in the undulators, whose effects are not included in the figures, may also lower the brightness somewhat. Second, to accommodate the possible use of clearing electrodes in the storage ring, the minimum undulator gap has been increased by 1 mm. This increase requires that the period of the short-wavelength undulator also be increased to 3.9 cm to avoid undesirable gaps in the spectral coverage. Third, undulator U8.0 now serves the low-photon-energy end of the ALS spectrum. The use of U8.0 to provide low-energy photons requires that it operate with a high value of K . The high K value means that U8.0 also generates substantial fluxes of higher harmonics, so that beam lines must be designed to handle this radiation. Finally, we plan to use the fifth harmonic of the undulators in addition to the first and third, thereby extending the undulator spectral range.

Table 4-1. Parameters for a possible initial complement of insertion devices for the ALS.

Name	Period (cm)	No. of periods	Photon energy range (eV) ^a	Critical energy (keV)
Undulators				
U8.0	8.0	61	5.4–220 ^b [16.2–660] [27–1100]	–
U5.0	5.0	98	52–380 [156–1140] [260–1900]	–
U3.9	3.9	123	169–500 [507–1500] [845–2500]	–
Wiggler				
W13.6	13.6	16	–	3.1

^aThe photon energy range of the fundamental and of the third and fifth harmonics (shown in brackets) as the deflection parameter K decreases from its maximum value to approximately 0.5, when the electron-beam energy is 1.5 GeV.

^bBelow about 8 eV in the fundamental, the peak field in undulator U8.0 exceeds the bending-magnet field and may affect storage-ring operation.

Figure 4-4 shows the fraction of the flux that is transversely coherent over the spectral range of the ALS undulators according to two criteria. The first is from statistical optics, namely, the fraction of coherent flux in a single Gaussian mode $[\mathcal{T}_c / \mathcal{T}_n]$ of Eq. (3-28). This fraction is a dimensionless ratio involving only the photon energy, the electron-beam emittance, and the undulator length. For practical optical systems, it is possible to use several radiation modes without significantly losing resolution, as reflected in the half-Airy-disk criterion [Goodman, 1985]. This criterion allows the acceptance of about six times more flux than the Gaussian-mode criterion, although at the diffraction-limited end of the spectrum it becomes unphysical, allowing more than 100% of the radiation to be coherent.

Table 4-2 contains detailed information on the undulators, wigglers, and bending magnets.

Fig. 4-1. Spectral flux as a function of photon energy for the three undulators and one wiggler described in Table 4-1, together with the bending magnets of the ALS. For the wiggler and bending magnets, we assume a 5-mr collection angle. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap, and represents the envelope of the first, third, and fifth, harmonics.

Fig. 4-2. Spectral brightness as a function of photon energy for the three undulators and one wiggler described in Table 4-1, together with the ALS bending magnets. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap, and represents the envelope of the first, third, and fifth harmonics.

Fig. 4-3. Spectral brightness as a function of photon energy for the three undulators described in Table 4-1. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gaps. Separate curves are shown for the first, third, and fifth harmonics of each undulator. The dotted extension of the first harmonic of U8.0 represents the performance when the undulator field exceeds the bending-magnet field.

Fig. 4-4. Fraction of the flux that is transversely coherent by the single-Gaussian-mode criterion $\bar{\epsilon}_x, \bar{\epsilon}_y$ of Eq. (3-28) (solid line) and by the half-Airy-disk criterion (dashed line), over the spectral range of the three undulators of Table 4-1.

Table 4-2 (following pages). Detailed performance characteristics of the four insertion devices of Table 4-1 and the ALS bending magnets, all at an electron energy of 1.5 GeV: (a) undulator U8.0; (b) undulator U5.0; (c) undulator U3.9; (d) wiggler W13.6; and (e) bending magnets. For the undulators, characteristics are given for the fundamental and for the third and fifth harmonics, for several values of K . The symbols used are explained below. The magnetic performance of the insertion devices was calculated by assuming a hybrid structure based on neodymium-iron.

BO (T)	Peak magnetic field for undulators and wigglers.
BRI	Spectral brightness, i.e., flux per unit phase-space area [photons/(s-mm ² -mr ² -0.1% bandwidth)].
E (GeV)	Beam energy.
ECR (keV)	Critical energy for wigglers and bending magnets.
EP (keV)	Photon energy.
F	Spectral flux. For undulators the flux in the central cone: (for wigglers and bending magnets, the flux within a 5-mr horizontal angle and all vertical angles [photons/(s-0.1% bandwidth)]).
FDEN1	Spectral flux per unit horizontal angle [photons/(s-mr-0.1% bandwidth)].
FDEN2	Spectral flux per unit solid angle [photons/(s-mr ² -0.1% bandwidth)].
I (A)	Beam current.
K	Peak deflection parameter for undulators.
LAMDW (cm)	Period length of undulators and wigglers.
N	Number of magnet periods (undulators and wigglers).
n	Harmonic number for undulator radiation.
NPOLE	Number of wiggler poles.
PCEN (W)	Power transmitted through a pinhole whose angular size is equal to that of the central angular cone at the fundamental frequency.
PDEN1	Power emitted (all frequencies) per unit horizontal angle W/mr .
PDEN2	Power emitted (all frequencies) per unit solid angle W/mr^2 .
PTOT (kW)	Total power (all angles and all frequencies) emitted by undulators and wigglers.
RHO (m)	Radius of curvature of electron beam in a bending magnet.
SIGPX (mr)	Horizontal rms beam divergence in the straight section.
SIGPY (mr)	Vertical rms beam divergence in the straight section.
SIGX (mm)	Horizontal rms beam size in the straight section.
SIGY (mm)	Vertical rms beam size in the straight section.
XLEN (m)	Length of undulators and wigglers.

Table 4-2a. Undulator U8.0.

E(CeV)	I(Amp)	SIGX(mm)	SIGY(mm)	SIGPX(mr)	SIGPY(mr)	N	LAMBDW(cm)	XLEN(m)
1.50	0.400	0.330	0.063	0.030	0.016	61	8.00	4.9
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
0.07	0.01	2.73E-04	2.22E+00		2.09E-02			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	2.66E-01	1.90E+13	2.01E+15		1.51E+16			
3	7.99E-01	2.39E+08	4.53E+10		3.44E+11			
5	1.33E+00	3.23E+03	7.31E+05		5.57E+06			
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
0.50	0.07	1.24E-02	7.21E+01		7.33E-01			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	2.37E-01	7.32E+14	7.16E+16		5.37E+17			
3	7.12E-01	1.47E+13	2.66E+15		2.02E+16			
5	1.19E+00	3.24E+11	7.08E+13		5.40E+14			
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
1.20	0.16	7.17E-02	2.06E+02		2.84E+00			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	1.55E-01	2.29E+15	1.65E+17		1.23E+18			
3	4.66E-01	5.53E+14	8.12E+16		6.15E+17			
5	7.76E-01	1.54E+14	2.87E+16		2.18E+17			
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
7.80	1.04	3.03E+00	1.40E+03		2.67E+02			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	8.50E-03	3.38E+15	1.75E+16		9.01E+16			
3	2.55E-02	2.22E+15	3.32E+16		2.15E+17			
5	4.25E-02	1.83E+15	4.41E+16		3.03E+17			
<hr/>								
K*	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
9.94	1.33	4.92E+00	1.78E+03		5.43E+02			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	5.30E-03	3.38E+15	1.10E+16		4.86E+16			
3	1.59E-02	2.22E+15	2.12E+16		1.27E+17			
5	2.65E-02	1.83E+15	2.85E+16		1.96E+17			

* At this value of K, the undulator magnetic field exceeds the bending-magnet field and may affect storage ring operation

Table 4-2b. Undulator U5.0.

E(GeV)	I(Amp)	SIGX(mm)	SIGY(mm)	SIGPX(mr)	SIGPY(mr)	N	LAMBDW(cm)	XLEN(m)
1.50	0.400	0.330	0.063	0.030	0.016	98	5.00	4.9
.....								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
0.05	0.01	2.83E-04	2.32E+00		1.64E-02			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	4.27E-01	1.24E+13	1.74E+15		1.31E+16			
3	1.28E+00	2.54E+07	5.69E+09		4.34E+10			
5	2.13E+00	5.59E+01	1.43E+04		1.09E+05			
.....								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
0.50	0.11	3.20E-02	1.85E+02		1.40E+00			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	3.80E-01	1.18E+15	1.55E+17		1.17E+18			
3	1.14E+00	2.37E+13	5.11E+15		3.90E+16			
5	1.90E+00	5.21E+11	1.30E+14		9.91E+14			
.....								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
1.20	0.26	1.84E-01	5.30E+02		5.21E+00			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	2.48E-01	3.68E+15	3.72E+17		2.79E+18			
3	7.45E-01	8.88E+14	1.63E+17		1.24E+18			
5	1.24E+00	2.47E+14	5.48E+16		4.18E+17			
.....								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))		PCEN(W)			
3.82	0.82	1.87E+00	1.75E+03		6.03E+01			
n	EP(keV)	F(#/s,0.1%BW)	FDEN2		BR1			
1	5.15E-02	5.37E+15	1.55E+17		1.08E+18			
3	1.55E-01	3.39E+15	2.45E+17		1.81E+18			
5	2.58E-01	2.67E+15	2.77E+17		2.08E+18			

Table 4-2c. Undulator U3.9.

E(GeV)	I(Amp)	SIGX(mm)	SIGY(mm)	SIGPX(mr)	SIGPY(mr)	N	LAMBDW(cm)	XLEN(m)
1.50	0.400	0.330	0.063	0.030	0.016	123	3.90	4.8
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)				
0.03	0.01	1.85E-04	1.52E+00	9.56E-03				
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI				
1	5.48E-01	6.33E+12	1.00E+15	7.60E+15				
3	1.64E+00	2.16E+06	5.17E+08	3.94E+09				
5	2.74E+00	7.91E-01	2.12E+02	1.62E+03				
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)				
0.50	0.14	5.15E-02	2.98E+02	1.99E+00				
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI				
1	4.87E-01	1.48E+15	2.20E+17	1.67E+18				
3	1.46E+00	2.97E+13	6.88E+15	5.25E+16				
5	2.43E+00	6.53E+11	1.71E+14	1.31E+15				
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)				
1.20	0.33	2.97E-01	8.53E+02	7.25E+00				
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI				
1	3.19E-01	4.62E+15	5.40E+17	4.07E+18				
3	9.56E-01	1.11E+15	2.24E+17	1.71E+18				
5	1.59E+00	3.10E+14	7.35E+16	5.61E+17				
<hr/>								
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)				
2.12	0.58	9.26E-01	1.54E+03	2.02E+01				
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI				
1	1.69E-01	6.23E+15	4.73E+17	3.52E+18				
3	5.06E-01	3.17E+15	4.82E+17	3.65E+18				
5	8.44E-01	1.95E+15	3.74E+17	2.85E+18				

Table 4-2d. Wiggler 13.6.

	E(GeV) 1.50	I(Amp) 0.400	SiGX(mm) 0.330	SiGY(mm) 0.063	SIGPX(mr) 0.030	SIGPY(mr) 0.016
NPOLE 32	LAMBDW(cm) 13.60	XLEN(m) 2.18	B0(T) 2.07	ECR(keV) 3.10	PTOT(kW) 5.31E+00	PDEN2(W/(mr**2)) 7.27E+02
	EP(keV)	F	FDEN1	FDEN2	BRI	
	5.000E-03	5.878E+14	1.176E+14	1.529E+13	9.123E+13	
	1.000E-02	7.355E+14	1.471E+14	2.426E+13	1.448E+14	
	5.000E-02	1.212E+15	2.425E+14	7.070E+13	4.219E+14	
	1.000E-01	1.477E+15	2.953E+14	1.116E+14	6.660E+14	
	5.000E-01	2.083E+15	4.166E+14	3.060E+14	1.825E+15	
	1.000E+00	2.161E+15	4.321E+14	4.384E+14	2.614E+15	
	3.098E+00*	1.537E+15	3.073E+14	5.551E+14	3.305E+15	
	5.000E+00	9.720E+14	1.944E+14	4.541E+14	2.699E+15	
	1.000E+01	2.482E+14	4.963E+13	1.688E+14	9.986E+14	
	2.000E+01	1.298E+13	2.597E+12	1.282E+13	7.508E+13	
	5.000E+01	1.218E+09	2.437E+08	1.935E+09	1.102E+10	
	1.000E+02	1.890E+02	3.780E+01	3.828E+02	2.120E+03	

Table 4-2e. Bending Magnets.

E(GeV) 1.50	I(Amp) 0.400	ETAX(m) 0.094	SICE 1.00E-03		
EMTX(mm*mr) 1.00E-02	EMTY(mm*mr) 1.00E-03	BETAX(m) 8.55E-01	ALPHAX 3.97E-01	BETAY(m) 1.46E+00	ALPHAY 1.08E-01
RHO(m) 4.81	B0(T) 1.04	ECR(keV) 1.56	PDEN1(W/mr) 5.90E+00	PDEN2(W/(mr**2)) 1.14E+01	
EP(keV)	F	FDEN1	FDEN2	BRI	
5.000E-04	1.081E+13	2.161E+12	1.599E+11	3.509E+12	
1.000E-03	1.359E+13	2.717E+12	2.585E+11	6.832E+12	
5.000E-03	2.295E+13	4.590E+12	7.557E+11	2.326E+13	
1.000E-02	2.860E+13	5.719E+12	1.199E+12	3.743E+13	
5.000E-02	4.608E+13	9.217E+12	3.477E+12	1.095E+14	
1.000E-01	5.492E+13	1.098E+13	5.445E+12	1.715E+14	
5.000E-01	6.753E+13	1.351E+13	1.367E+13	4.301E+14	
1.000E+00	5.995E+13	1.199E+13	1.717E+13	5.392E+14	
1.556E+00*	4.802E+13	9.603E+12	1.735E+13	5.433E+14	
5.000E+00	7.862E+12	1.572E+12	5.335E+12	1.642E+14	
1.000E+01	4.177E+11	8.354E+10	4.114E+11	1.234E+13	
2.000E+01	9.159E+08	1.832E+08	1.300E+09	3.716E+10	
5.000E+01	6.870E+00	1.374E+00	1.390E+01	3.651E+02	
1.000E+02	1.475E-13	2.949E-14	4.104E-13	9.556E-12	

*This is the critical energy.

5. Beam Lines

Synchrotron radiation was first used as a light source for scientific research in the 1950s, and its use has increased continuously since. Initially, researchers made parasitic use of synchrotrons that operated for other programs. Conventional spectrometers designed for discharge and spark sources were used and were generally coupled to light sources by glass optical systems. The photon beam power involved was usually small. In the decades that followed these early experiments, synchrotrons have been superseded by storage rings designed for optimum light output. Recently, the use of wigglers and undulators has further advanced light-source technology. During these years, there have also been corresponding developments in optical systems, and many specialized monochromators have been built.

For the optical designer, all these advances have created new challenges, especially in two areas:

- The source size has become smaller so that relay optics require tighter tolerances to avoid loss of light. The use of smaller slits also becomes practical so that monochromator components also need tighter tolerances to avoid loss of resolution. These tolerances apply to both optical figure and finish.
- The photon beam power has increased to the point that, in addition to satisfying more stringent surface tolerances, optical components must be cooled to control thermal distortions and stresses. This complicates the design and limits the choice of materials.

LBL has played a leading role in the design and use of high-power wigglers, and this has led to its involvement with Exxon and SSRL in the construction of a 54-pole wiggler, together with the beam line [Bahr et al., 1983] needed to exploit this device, at the SPEAR storage ring at Stanford. The chief conclusion from that exercise was that when a large heat load is present it dominates the design and cost of the beam line. The difficulties of dealing with large heat load have increased interest in the properties of undulators, which usually generate lower total power than wigglers. In addition, most of the unwanted power in undulator radiation can be dumped in a nonoptical component (a pinhole, for example), which is a great advantage. For the beam lines described here, the power problem is usually quite moderate and, at worst, is similar to that of the 54-pole wiggler beam line. Our strategy for dealing with it is to use pinholes where appropriate, plus active water cooling of the optics.

tions, we use the analysis of the imaging performance of a grating in terms of the optical-path function. We consider only the case of a toroidal surface [Haber, 1950; Noda et al., 1974] (of which the spherical is a special case), and we write the optical-path function as a power-series expansion in the aperture coordinates w and ℓ defined in Fig. 5-1:

$$F = F_{000} + wF_{100} + \ell F_{011} + w\ell F_{111} + \frac{1}{2}wF_{102} + \frac{1}{2}w^2F_{200} \\ + \frac{1}{2}\ell^2F_{020} + \frac{1}{2}w\ell^2F_{120} + \frac{1}{2}w^3F_{300} + \frac{1}{8}w^4F_{400} + \cdots + w^j\ell^jF_{jjk} + \cdots \quad (5-1)$$

where

$$F_{000} = \sum r \quad \text{Constant term} \quad (5-2a)$$

$$F_{100} = \frac{m\lambda}{d} - \sum \sin \alpha \quad \text{Grating equation} \quad (5-2b)$$

$$F_{011} = - \sum \frac{\Delta z}{r} \quad \text{Magnification} \quad (5-2c)$$

$$F_{111} = - \sum \frac{\Delta z \sin \alpha}{r^2} \quad \text{Line shape} \quad (5-2d)$$

$$F_{102} = \sum \frac{\Delta z^2 \sin \alpha}{r^2} \quad \text{Line shape} \quad (5-2e)$$

$$F_{200} = \sum T \quad \text{Focus} \quad (5-2f)$$

$$F_{020} = \sum S \quad \text{Astigmatism} \quad (5-2g)$$

$$F_{120} = \sum \frac{S \sin \alpha}{r} \quad \text{Astigmatic coma} \quad (5-2h)$$

$$F_{300} = \sum \frac{T \sin \alpha}{r} \quad \text{Primary coma} \quad (5-2i)$$

$$F_{400} = \sum \left(\frac{4T \sin^2 \alpha}{r^2} - \frac{T^2}{r} + \frac{S}{R^2} \right) \quad \text{Spherical aberration} \quad (5-2j)$$

with

$$T = \frac{\cos^2 \alpha}{r} - \frac{\cos \alpha}{R}$$

$$S = \frac{1}{r} - \frac{\cos \alpha}{\rho}$$

The parameter α is the incidence angle, β is the diffraction angle, m is the spectral order, d is the groove spacing, and R and ρ are the major and minor radii of the toroid, respectively. The meaning of the summation sign is that a second term must be added that is identical to the first, apart from the replacements $\alpha \rightarrow \beta$, $r \rightarrow r'$, $\Delta z \rightarrow \Delta z'$.

We see that each term of F represents a type of image imperfection or aberration. It is possible to derive from F the details of the x-ray distribution in the image (exit-slit) plane due to a point source in the object (entrance-slit) plane. This is the impulse response (or spread function) of the system. The art of optical design is to achieve the smallest possible line spread in the dispersion direction (to get good resolution), while maintaining a high phase-space acceptance for the instrument.

To get a perfect image, all the F_{ijk} would need to be zero, a goal that cannot be achieved for any grating surface. To be in focus, it is necessary that $F_{200} = 0$. One way to achieve this is by setting $r = R \cos \alpha$ and $r' = R \cos \beta$, i.e., the entrance and exit slits lie on the Rowland circle. If this is done, then F_{300} is also identically zero. For all choices of in-focus grazing-incidence configurations, including the Rowland circle, it happens that astigmatism (where a point is imaged to a line) can be corrected by the grating only if a steeply curved toroid is used. This would be done by choosing ρ so that $F_{020} = 0$. Given our choice of all-spherical surfaces, $\rho = R$, and astigmatism cannot be corrected by the grating.

This does not prevent the achievement of good resolution, however. It can be shown that for a spherical grating the line curvature originating from F_{111} , F_{102} , and F_{120} —which is very troublesome with toroids—is, in cases of interest to us, negligible compared with spherical aberration. In addition, the spherical aberration is itself small compared with diffraction if the grating is fairly small, as would be the case for an undulator beam line. Thus, in principle, our spherical gratings can be diffraction limited. In practice, the goal of the fabricator will be to achieve tolerances consistent with the use of 10- μm slits in our systems, which means a tolerance of around 1 μrad . This has been achieved in the past for standard spherical gratings [Ito et al., 1986], although it is far out of reach for aspherics.

To summarize, we conclude that our choice of spherical surfaces as the safest from a manufacturing viewpoint also has many advantages from an optical viewpoint. The chief disadvantage is a large astigmatism, which we can overcome using the properties of the condensing system. We discuss this in Section 5.3.1.

To evaluate the slit-width-limited resolution for a grating monochromator, we note that we must have $F_{100} = 0$ or

$$m\lambda = d (\sin \alpha + \sin \beta), \quad (5-3)$$

which is the grating equation. From this, one can show that the resolution $\Delta\lambda_s$ due to a slit of width s is given by

$$\Delta\lambda_s = \frac{sd \cos \alpha}{r}. \quad (5-4)$$

The one-dimensional phase-space acceptance A is defined as

$$A = W \Delta\theta \cos \alpha, \quad (5-5)$$

where $\Delta\theta$ is the acceptance angle of the spectrometer and W is the width of the diffracting element. One can now derive from Eq. (5-4) that A is given by

$$A = N \Delta\lambda_s, \quad (5-6)$$

where N is the total number of grooves.

5.1.2 Crystal Monochromators. Both grating and crystal monochromators are essentially multiple-beam interferometers. A grating produces N beams by dividing the wave front of the incoming light; a crystal or artificial multilayer does it by dividing the amplitude.

The fundamental law governing the operation of a crystal monochromator is the Bragg equation:

$$n\lambda = 2d \sin \theta, \quad (5-7)$$

where n is the order of reflection, d is the crystal period, and θ is the angle of glancing incidence. In addition, unlike the case of a diffraction grating, the law of reflection must be satisfied; i.e., the angle of incidence must equal the angle of reflection.

For a crystal spectrometer, the angular acceptance $\Delta\theta$ is the angular width of the Bragg diffraction peak. For a given wavelength and crystal, this quantity is essentially fixed. This leads to a much-reduced ability to manipulate the resolution/flux trade-off, as compared with gratings.

Differentiating the Bragg equation, we see that

$$\frac{\lambda}{\Delta\lambda} = \frac{\tan \theta}{\Delta\theta}, \quad (5-8)$$

and inserting Eq. (5-5), we get

$$A = W \sin \theta \tan \theta \frac{\Delta\lambda}{\lambda}. \quad (5-9)$$

For a double-crystal spectrometer, the value of $\Delta\theta$ is about $1/\sqrt{2}$ times that for a single crystal. Later, in Fig. 5-7, we plot Δ versus λ for two of the higher-resolution crystals that would be used in this region, beryl ($2d = 15.94 \text{ \AA}$) and germanium (111) ($2d = 6.532 \text{ \AA}$). It follows from Eq. (5-9) that lower-resolution crystals have higher Δ values. In particular, multilayers, which could cover the 250- to 800-eV region, have $\lambda/\Delta\lambda \approx 30$ and thus have an even-larger phase-space acceptance.

The general conclusion is that, for both wigglers and bending magnets, all of the crystals of practical interest have a phase-space acceptance that is comfortably able to accept the entire beam.

5.2 User Requirements

We describe in this section beam-line designs that match the undulators and wiggler reviewed in Section 4. With only four beam lines, it is not possible to provide every type of service requested by every possible user; consequently, the strategy adopted is to describe general-purpose beam lines. We try to provide (conceptually) as wide a range of service as possible with this initial complement of beam lines, while keeping in mind the spectral region to which the ALS is primarily directed, namely, the VUV and soft x-ray regions. In light of this, it is apparent that one cannot initially have separate high-flux and high-resolution facilities. Each monochromator must be flexible enough to provide both of these services. For diffraction-grating monochromators on undulator beam lines, we know how to do this. The physics of crystal optical systems, however, makes the goal of flexibility harder to achieve, although artificial multilayer devices are beginning to improve the situation.

After studying the wavelength-coverage, resolution, flux, and polarization requirements of the various user groups, we adopted the set of insertion devices described in Section 4 and the corresponding beam lines described in Table 5-1. We note that to obtain an undulator with a wide spectral coverage one must use a wide range of K values. At large values of K , the undulators generate substantial fluxes of radiation at high harmonics, and the beam-line optical system must be able to handle this "extra" radiation. Below, we describe the optical systems that provide the capability outlined in Table 5-1.

Ongoing work is aimed at refining many of the computations that underlie the values tabulated in Tables 5-1, 5-2, and 5-3 and shown in the performance plots in this section. Nonetheless, the complement of beam lines described here remains a useful guide to the properties of radiation that can be expected on target at the ALS.

5.3 Optical Systems

We are proposing two types of optical systems:

- The Rense and Violett spherical-grating monochromator system (which we use in three beam lines).
- A soft x-ray crystal monochromator.

These are described in the following sections.

Table 5-1. Summary of parameters for the four insertion-device beam lines discussed in the text. The scientific applications listed are based on the findings of ALS topical workshops and are examples only; many other applications are possible.

Radiation source ^a	Max aperture		Beam-line spectral range (eV)	Energy resolution at a representative energy (eV) ^b	Monochromator type ^c	Examples of scientific applications
	H (mrad)	V(mrad)				
U8.0	0.55	0.55	5.4-200	0.0013 (@ 56)	10° SGM	Chemistry, low-energy surface science, atomic and molecular spectroscopy
U5.0	0.185	0.18	52-800	0.02 (@ 280)	2.9° SGM	Core-level spectroscopy, EXAFS, atomic and molecular spectroscopy
U3.9	0.1	0.09	180-1000	0.3 (@ 540)	2° SGM	Imaging, biology, advanced lithography, spectroscopy
W13.6	18.0	0.85	800-3500	0.5 (@ 1840)	Crystal	Core-level spectroscopy, EXAFS, NEXAFS, protein crystallography,
			3000-10,000		Vacant	materials microbeam characterization

^aU = undulator, W = wiggler, (xx.x) = period length in cm.

^bFor undulators, resolution is slit-width limited with 10- μ m slit.

^cSGM = spherical-grating monochromator.

Table 5-2. Optical-component parameters for the four beam lines of Table 5-1

Beam line	Type	Premirror system						Type	Monochromator			
		α (deg)	Mirror size (mm)	Imaging conjugates r, r (m)		Central cone power			Incidence angle at zero order (deg)	Grating size (mm)	Grating radius (m)	Nominal conjugates r, r (m)
				H	V	Total (W)	Density (W/mr ²)					
U80	2 spherical mirrors in K-B mount	82.5	300×25	15, 7.5	15.5, 1.0	540	1780	Spherical grating with constant deviation	80	180×50	17.3	17, 4.3
U50	-	89.0	300×25	15, 7.5	15.5, 1.0	60	1750	-	87.1	180×50	57.3	18, 4.2
U39	-					20	1540	-	88	180×50	320	16, 6.72
W136	-	89.0	1000×100 500×100	10.4, 17.8	9.4, 18.8			Double crystal		25×25 (crystal)		

Symbols and abbreviations: α = angle of incidence, K-B = Kirkpatrick-Baez, H = horizontal, V = vertical

Table 5-3 (following pages). Beam-line and diffraction-grating monochromator efficiency worksheets for undulator beam lines: (a) U8.0, (b) U5.0, and (c) U3.9. The information below applies to all three beam lines.

• **Advanced Light Source Parameters**

Nominal Electron Energy (E)	1.5 GeV
Electron-beam current (I)	400 mA

• **Insertion Device Source Parameters**

Vertical rms e-beam size (SIGY)	0.063 mm
Horizontal rms e-beam size (SIGX)	0.330 mm
Vertical rms e-beam divergence (SIGPY)	0.016 mr
Horizontal rms e-beam divergence (SIGPX)	0.030 mr

• Computed bandwidths are based on the slit width limited resolution. Optical fabrication tolerances, thermal distortion, and optical aberrations are not accounted for. Slit widths are set to the minimum specified width or set to match the diffraction-limited image of the source.

• Tabulations are the output of a "Microsoft EXCEL" spreadsheet program, which is available on request to those who wish to obtain similar information for other input data.

• Optical constants are taken from the following sources:

- [1] B. L. Henke, et al, *Atomic Data and Nuclear Data Tables*, **27**, 1 (1982).
- [2] D.L. Windt, et al, *Applied Optics*, **27**, 246 (1988).
- [3] J.H. Weaver, et al, *Physik Daten, Physics Data*, "Optical Properties of Metals," Vol. 18-1 (Fach-information Zentrum, Karlsruhe, 1981).
- [4] J.H. Weaver, et al, *Physik Daten, Physics Data*, "Optical Properties of Metals," Vol. 18-2 (Fach-information Zentrum, Karlsruhe, 1981).

Table 5-3a.

U 8.0 Beam Line		Synchrotron Radiation Source:		Spherical Grating Monochromator:				
7.5 deg. M1 & M2 10.0 deg. SGM		U	• Source Type (U, W, or "BM")	1 0	• deg. SGM			
		8.00	• Period Length [cm]	160.00	• Included Angle (2 θ) [deg]			
		6 1	• Number of Periods	1	• Diffracted order (m)			
		4.88	• Source Length [m]	0.065	• Magnification of Condensing Mirror System			
Grating Parameters	Photon Wavelength	Photon Energy	Source Flux	Undulator Harmonic	M1 Mirror Reflectance	M2 Mirror Reflectance	Transmitted Flux	Length from Entr. Slit to Grating (r)
	[Å]	[eV]	phot/sec 0.1% bw	n			photons/sec 0.1% bw	[m]
G1	60	206.6	1.40E+15	1	0.231	0.231	7.43E+13	1.70
1200	• lines/mm	100	2.70E+15	1	0.728	0.728	1.43E+15	1.70
	Blaze Wavelength	140	3.04E+15	1	0.698	0.698	1.48E+15	1.70
2.8	(deg) Blaze Angle	180	3.18E+15	1	0.674	0.674	1.44E+15	1.70
	Optical Coating:	220	3.25E+15	1	0.619	0.619	1.24E+15	1.70
7 9	• At. Number	240	3.27E+15	1	0.623	0.623	1.27E+15	1.70
Gold	Material	260	3.29E+15	1	0.644	0.644	1.36E+15	1.70
503 Å	Horizon wavelength	320	3.31E+15	1	0.674	0.674	1.51E+15	1.70
(24.67)	eV	400	3.35E+15	1	0.621	0.621	1.29E+15	1.70
G2	120	103.3	2.92E+15	1	0.742	0.742	1.61E+15	1.70
600	• lines/mm	200	3.22E+15	1	0.639	0.639	1.32E+15	1.70
	Blaze Wavelength	280	3.30E+15	1	0.657	0.657	1.43E+15	1.70
2.8	(deg) Blaze Angle	360	3.34E+15	1	0.660	0.660	1.45E+15	1.70
	Optical Coating:	440	3.35E+15	1	0.634	0.634	1.35E+15	1.70
7 9	• At. Number	580	3.37E+15	1	0.601	0.601	1.22E+15	1.70
Gold	Material	640	3.37E+15	1	0.578	0.578	1.12E+15	1.70
1005 Å	Horizon wavelength	700	3.37E+15	1	0.593	0.593	1.19E+15	1.70
(12.34)	eV	800	3.38E+15	1	0.594	0.594	1.19E+15	1.70
G3	360	34.4	2.92E+15	1	0.660	0.660	1.27E+15	1.70
200	• lines/mm	600	3.22E+15	1	0.572	0.572	1.05E+15	1.70
	Blaze Wavelength	840	3.30E+15	1	0.588	0.588	1.14E+15	1.70
2.8	(deg) Blaze Angle	1080	3.34E+15	1	0.572	0.572	1.09E+15	1.70
	Optical Coating:	1320	3.35E+15	1	0.560	0.560	1.05E+15	1.70
7 9	• At. Number	1560	3.37E+15	1	0.572	0.572	1.10E+15	1.70
Gold	Material	1700	3.37E+15	1	0.567	0.567	1.09E+15	1.70
3015 Å	Horizon wavelength	2000	3.37E+15	1	0.588	0.588	1.17E+15	1.70
(4.11)	eV	2300	3.38E+15	1	0.596	0.596	1.20E+15	1.70

Table 5-3a. (continued)

U 8.0 Beam Line		Gratings:		180	• Grating Width [mm]		
				B	• Blazed [B] or Lamella [L] gratings		
				V	• Fixed [F] or Variable [V] slit width (variable slit is matched to the diffraction limited image of the source.)		
7.5 deg. M1 & M2				10	• Slit width (if Fixed), or Minimum slit width (if Variable)		
10.0 deg. SGM							

Table 5-3a. (continued)

U 8.0 Beam Line 7.5 deg. M1 & M2 10.0 deg. SGM		Condensing Mirrors:		M1	M2	<ul style="list-style-type: none"> Mirror Grazing Incidence Angle (deg.) (Use 0.0 deg. angle if there is no mirror) Mirror Coating Mat'l Atomic Number Mirror Coating Mat'l Name 			
				7.50	7.50				
Grating Parameters		Photon Wavelength (Å)	Diff. Limited Source FWHM (vertical) (microns)	FWHM Image Size at Entr. Slit (microns)	Entrance Slit Width (vertical) (microns)	Slit Transmission Factor (Image/Slit)	Slit Width Limited $\Delta\lambda_s$ (Å)	Fractional Bandwidth $\Delta\lambda_s/\lambda$	Resolving Power $\lambda/\Delta\lambda_s$
G1		60	151.5	9.8	10.0	1.00	0.0074	1.2e-04	8.1e+03
1200	• lines/mm	100	153.7	10.0	10.0	1.00	0.0068	6.8e-05	1.5e+04
	Blaze Wavelength	140	155.9	10.1	10.1	1.00	0.0062	4.5e-05	2.2e+04
2.8	(deg) Blaze Angle	180	158.1	10.3	10.3	1.00	0.0056	3.1e-05	3.2e+04
	Optical Coating:	220	160.2	10.4	10.4	1.00	0.0050	2.3e-05	4.4e+04
79	• At. Number	240	161.3	10.5	10.5	1.00	0.0047	2.0e-05	5.1e+04
	Gold	260	162.3	10.6	10.6	1.00	0.0044	1.7e-05	6.0e+04
503 Å (24.67)	Horizon wavelength	320	165.5	10.8	10.8	1.00	0.0034	1.0e-05	9.5e+04
	eV	400	169.5	11.0	11.0	1.00	0.0019	4.8e-06	2.1e+05
G2		120	154.8	10.1	10.1	1.00	0.0151	1.3e-04	7.9e+03
600	• lines/mm	200	159.2	10.3	10.3	1.00	0.0142	7.1e-05	1.4e+04
	Blaze Wavelength	280	163.4	10.6	10.6	1.00	0.0131	4.7e-05	2.1e+04
2.8	(deg) Blaze Angle	360	167.5	10.9	10.9	1.00	0.0120	3.3e-05	3.0e+04
	Optical Coating:	440	171.5	11.2	11.2	1.00	0.0107	2.4e-05	4.1e+04
79	• At. Number	580	178.4	11.6	11.6	1.00	0.0084	1.5e-05	6.9e+04
	Gold	640	181.2	11.8	11.8	1.00	0.0074	1.1e-05	8.7e+04
1005 Å (12.34)	Horizon wavelength	700	184.0	12.0	12.0	1.00	0.0062	8.9e-06	1.1e+05
	eV	800	188.6	12.3	12.3	1.00	0.0043	5.4e-06	1.9e+05
G3		360	167.5	10.9	10.9	1.00	0.0491	1.4e-04	7.3e+03
200	• lines/mm	600	179.3	11.7	11.7	1.00	0.0478	8.0e-05	1.3e+04
	Blaze Wavelength	840	190.4	12.4	12.4	1.00	0.0458	5.5e-05	1.8e+04
2.8	(deg) Blaze Angle	1080	200.9	13.1	13.1	1.00	0.0430	4.0e-05	2.5e+04
	Optical Coating:	1320	210.8	13.7	13.7	1.00	0.0396	3.0e-05	3.3e+04
79	• At. Number	1560	220.3	14.3	14.3	1.00	0.0356	2.3e-05	4.4e+04
	Gold	1700	225.7	14.7	14.7	1.00	0.0330	1.9e-05	5.2e+04
3015 Å (4.11)	Horizon wavelength	2000	236.8	15.4	15.4	1.00	0.0267	1.3e-05	7.5e+04
	eV	2300	247.3	16.1	16.1	1.00	0.0197	8.6e-06	1.2e+05

Table 5-3a. (continued)

U 8.0 Beam Line 7.5 deg. M1 & M2 10.0 deg. SCM									
Grating Parameters	Photon Wavelength [Å]	Resolved Bandwidth Ratio (actual/0.1%)	Grating Illuminated width [mm]	Monit' Acceptance (A) [m. rad]	Source Emission (Emi) [m. rad]	Flux Fraction Accepted (A)/(Emi)	Photon Energy [eV]	Resolved Flux Out Photons/sec $\Delta\lambda/\lambda$ fwh	
1200 * Blaze Wavelength: (deg) Blaze Angle: Optical Coating: * At. Number: GdD Material: 503 Å Horizon wavelength: (24.67) eV	G1	0.1232	15.5	1.60e-07	1.37e-08	1.00	206.6	1.29E+10	
	60	0.0683	21.2	1.48e-07	1.73e-08	1.00	124.0	1.91E+13	
	140	0.0446	27.3	1.35e-07	2.05e-08	1.00	88.6	2.30E+13	
	180	0.0314	34.4	1.22e-07	2.33e-08	1.00	68.9	1.34E+13	
	220	0.0228	43.2	1.08e-07	2.60e-08	1.00	56.4	5.94E+12	
79 * At. Number: GdD Material: 503 Å Horizon wavelength: (24.67) eV	240	0.0196	48.4	1.01e-07	2.73e-08	1.00	51.7	4.61E+12	
	260	0.0168	54.4	9.44e-08	2.65e-08	1.00	47.7	3.88E+12	
	320	0.0105	79.6	7.25e-08	3.21e-08	1.00	38.7	1.95E+12	
	400	0.0048	157.5	4.19e-08	3.56e-08	1.00	31.0	4.86E+11	
600 * Blaze Wavelength: (deg) Blaze Angle: Optical Coating: * At. Number: GdD Material: 1005 Å Horizon wavelength: (12.34) eV	G2	0.1259	20.9	1.63e-07	1.90e-08	1.00	103.3	2.98E+12	
	120	0.0708	29.1	1.53e-07	2.47e-08	1.00	62.0	1.58E+13	
	280	0.0468	37.8	1.41e-07	2.97e-08	1.00	44.3	2.16E+13	
	360	0.0332	47.9	1.29e-07	3.44e-08	1.00	34.4	1.39E+13	
	440	0.0244	60.2	1.16e-07	3.88e-08	1.00	28.2	7.09E+12	
79 * At. Number: GdD Material: 1005 Å Horizon wavelength: (12.34) eV	580	0.0145	91.4	9.10e-08	4.62e-08	1.00	21.4	2.33E+12	
	640	0.0115	111.6	7.94e-08	4.92e-08	1.00	19.4	1.39E+12	
	700	0.0089	139.4	6.75e-08	5.23e-08	1.00	17.7	1.00E+12	
	800	0.0054	180.0	4.66e-08	5.72e-08	0.81	15.5	3.94E+11	
200 * Blaze Wavelength: (deg) Blaze Angle: Optical Coating: * At. Number: GdD Material: 3015 Å Horizon wavelength: (4.11) eV	G3	0.1363	35.1	1.77e-07	3.44e-08	1.00	30.4	2.22E+12	
	600	0.0797	44.4	1.72e-07	4.72e-08	1.00	20.7	1.25E+13	
	840	0.0545	64.6	1.65e-07	5.91e-08	1.00	14.8	1.76E+13	
	1080	0.0398	82.1	1.55e-07	7.06e-08	1.00	11.5	1.07E+13	
	1320	0.0300	103.3	1.43e-07	8.19e-08	1.00	9.4	5.93E+12	
79 * At. Number: GdD Material: 3015 Å Horizon wavelength: (4.11) eV	1560	0.0228	130.6	1.28e-07	9.29e-08	1.00	7.9	3.78E+12	
	1700	0.0194	150.7	1.19e-07	9.93e-08	1.00	7.3	2.73E+12	
	2000	0.0134	180.0	9.62e-08	1.13e-07	0.85	6.2	1.38E+12	
	2300	0.0086	180.0	7.09e-08	1.27e-07	0.56	5.4	4.67E+11	

Table 5-3b.

U 5.0 Beam Line		Synchrotron Radiation Source:			Spherical Grating Monochromator:				
1.0 deg. M1 & M2 2.87 deg. SGM		U • Source Type (U, W, or "BM") 5.00 • Period Length [cm] 98 • Number of Periods 4.90 • Source Length [m]			2.87 • deg. SGM 174.26 • Included Angle (2 θ) [deg.] 1 • Diffracted order (m) 0.065 • Magnification of Condensing Mirror System				
Grating Parameters		Photon Wavelength [Å]	Photon Energy [eV]	Source Flux phot/sec 0.1% bw	Undulator Harmonic n	M1 Mirror Reflectance	M2 Mirror Reflectance	Transmitted Flux photons/sec 0.1% bw	Length from Entr. Slit to Grating (r) [m]
G1		12	1033.2	1.17E+14	3	0.787	0.787	7.24e+13	1.80
1100	• lines/mm	15	826.6	5.93E+14	3	0.771	0.771	3.53e+14	1.80
	Blaze Wavelength	17	729.3	9.54E+14	3	0.770	0.770	5.65e+14	1.80
1.1	(deg) Blaze Angle	20	619.9	1.44E+15	3	0.770	0.770	8.53e+14	1.80
	Optical Coating:	22	563.6	1.71E+15	3	0.771	0.771	1.02e+15	1.80
79	• At. Number	25	495.9	2.04E+15	3	0.773	0.773	1.22e+15	1.80
Gold	Material	28	442.8	2.30E+15	3	0.781	0.781	1.40e+15	1.80
46 Å	Horizon wavelength	31	400.0	2.50E+15	3	0.792	0.792	1.57e+15	1.80
(272.01)	eV	35	354.2	2.71E+15	3	0.802	0.802	1.74e+15	1.80
G2		26	476.9	2.13E+15	3	0.775	0.775	1.28e+15	1.80
500	• lines/mm	31	400.0	2.50E+15	3	0.792	0.792	1.57e+15	1.80
	Blaze Wavelength	37	335.1	2.79E+15	3	0.807	0.807	1.82e+15	1.80
1.1	(deg) Blaze Angle	42	295.2	2.95E+15	3	0.821	0.821	1.99e+15	1.80
	Optical Coating:	48	258.3	3.09E+15	3	0.832	0.832	2.14e+15	1.80
28	• At. Number	58	213.8	4.15E+15	1	0.850	0.850	3.00e+15	1.80
Nickel	Material	65	190.7	4.42E+15	1	0.866	0.866	3.32e+15	1.80
100 Å	Horizon wavelength	80	155.0	4.78E+15	1	0.942	0.942	4.24e+15	1.80
(123.64)	eV	90	137.8	4.92E+15	1	0.959	0.959	4.53e+15	1.80
G3		65	190.7	4.42E+15	1	0.866	0.866	3.32e+15	1.80
200	• lines/mm	73	169.8	4.64E+15	1	0.909	0.909	3.84e+15	1.80
	Blaze Wavelength	92	134.8	4.94E+15	1	0.960	0.960	4.56e+15	1.80
1.1	(deg) Blaze Angle	100	124.0	5.02E+15	1	0.962	0.962	4.65e+15	1.80
	Optical Coating:	120	103.3	5.15E+15	1	0.963	0.963	4.78e+15	1.80
28	• At. Number	140	88.6	5.23E+15	1	0.955	0.955	4.77e+15	1.80
Nickel	Material	160	77.5	5.28E+15	1	0.955	0.955	4.82e+15	1.80
251 Å	Horizon wavelength	190	65.3	5.33E+15	1	0.945	0.945	4.76e+15	1.80
(49.46)	eV	220	56.4	5.35E+15	1	0.938	0.938	4.72e+15	1.80

Table 5-3b. (continued)

U 5.0 Beam Line		Gratings:		180 • Grating Width [mm] B • Blazed [B] or Lamella [L] gratings V • Fixed [F] or Variable [V] slit width (variable slit is matched to the diffraction limited image of the source.) 10 • Slit width (if Fixed), or Minimum slit width (if Variable)				
1.0 deg. M1 & M2 2.07 deg. SGM								
Grating Parameters	Photon Wavelength [Å]	Grating Diffraction Angles		Grating Reflectance R	"On-blaze" efficiency factor	Diffraction Efficiency/R	Absolute Diffraction Efficiency	
		β (normal)	α (normal)					
		[deg]	[deg]					
•								
G1		12	-86.3747	87.8853	0.300	0.457	0.5447	0.0747
1100 • lines/mm	Blaze Wavelength (deg) Blaze Angle	15	-86.1859	88.0741	0.385	0.457	0.9430	0.1658
1.1		17	-86.0600	88.2000	0.421	0.457	1.0000	0.1924
Optical Coating:		20	-85.8712	88.3888	0.465	0.457	0.9279	0.1975
79 • At. Number	Material	22	-85.7452	88.5148	0.492	0.457	0.8409	0.1890
Gold		25	-85.5564	88.7036	0.529	0.457	0.7050	0.1705
46 Å		28	-85.3675	88.8925	0.575	0.457	0.5844	0.1535
(272.01) eV	Horizon wavelength	31	-85.1786	89.0814	0.623	0.457	0.4849	0.1382
		35	-84.9267	89.3333	0.678	0.457	0.3817	0.1183
•								
G2		26	-86.3862	87.8738	0.729	0.461	0.5338	0.1796
500 • lines/mm	Blaze Wavelength (deg) Blaze Angle	31	-86.2431	88.0169	0.754	0.461	0.8828	0.3069
1.1		37	-86.0714	88.1886	0.767	0.461	1.0000	0.3538
Optical Coating:		42	-85.9284	88.3316	0.780	0.461	0.9541	0.3432
28 • At. Number	Material	48	-85.7567	88.5033	0.792	0.461	0.8384	0.3065
Nickel		58	-85.4705	88.7895	0.811	0.461	0.6362	0.2379
100 Å		65	-85.2702	88.9898	0.825	0.461	0.5201	0.1980
(123.64) eV	Horizon wavelength	80	-84.8408	89.4192	0.859	0.461	0.3453	0.1369
		90	-84.5544	89.7055	0.888	0.461	0.2694	0.1103
•								
G3		65	-86.3862	87.8738	0.742	0.464	0.5469	0.1880
200 • lines/mm	Blaze Wavelength (deg) Blaze Angle	73	-86.2946	87.9654	0.751	0.464	0.7963	0.2772
1.1		92	-86.0772	88.1828	0.778	0.464	1.0000	0.3608
Optical Coating:		100	-85.9856	88.2744	0.789	0.464	0.9790	0.3579
28 • At. Number	Material	120	-85.7567	88.5033	0.807	0.464	0.8329	0.3115
Nickel		140	-85.5278	88.7322	0.822	0.464	0.6680	0.2547
251 Å		160	-85.2988	88.9612	0.826	0.464	0.5299	0.2029
(49.46) eV	Horizon wavelength	190	-84.9553	89.3047	0.828	0.464	0.3794	0.1457
		220	-84.6117	89.6483	0.904	0.464	0.2794	0.1171

Table 5-3b. (continued)

U 5.0 Beam Line		Condensing Mirrors:			M 1	M 2	<ul style="list-style-type: none"> • Mirror Grazing Incidence Angle (deg.) (Use 0.0 deg. angle if there is no mirror) • Mirror Coating Mat'l Atomic Number • Mirror Coating Mat'l Name 		
1.0 deg. M1 & M2 2.87 deg. SGM					1.00	1.00			
					7.9 Gold	7.9 Gold			
Grating Parameters	Photon Wavelength	Diff. Limited Source FWHM (vertical)	FWHM Image Size at Entr. Slit (microns)	Entrance Slit Width (vertical) (microns)	Slit Flux Transmission Factor (Image/Slit)	Slit Width Limited $\Delta\lambda_s$ (Å)	Fractional Bandwidth $\Delta\lambda_s/\lambda$	Resolving Power $\lambda/\Delta\lambda_s$	
G1									
1100	• lines/mm	12	148.7	9.7	10.0	1.00	1.5e-04	6.7e+03	
	Blaze Wavelength	15	148.9	9.7	10.0	1.00	1.1e-04	9.1e+03	
1.1	(deg) Blaze Angle	17	149.0	9.7	10.0	1.00	9.0e-05	1.1e+04	
	Optical Coating:	20	149.2	9.7	10.0	1.00	6.9e-05	1.5e+04	
7.9	• At. Number	22	149.3	9.7	10.0	1.00	5.8e-05	1.7e+04	
Gold	Material	25	149.5	9.7	10.0	1.00	4.4e-05	2.3e+04	
46 Å	Horizon wavelength	28	149.7	9.7	10.0	1.00	3.4e-05	2.9e+04	
(272.01)	eV	31	149.8	9.7	10.0	1.00	2.5e-05	3.9e+04	
		35	150.1	9.8	10.0	1.00	1.6e-05	6.1e+04	
G2									
500	• lines/mm	26	149.5	9.7	10.0	1.00	1.5e-04	6.5e+03	
	Blaze Wavelength	31	149.8	9.7	10.0	1.00	1.2e-04	8.3e+03	
1.1	(deg) Blaze Angle	37	150.2	9.8	10.0	1.00	9.3e-05	1.1e+04	
	Optical Coating:	42	150.5	9.8	10.0	1.00	7.5e-05	1.3e+04	
2.8	• At. Number	48	150.8	9.8	10.0	1.00	5.9e-05	1.7e+04	
Nickel	Material	58	151.4	9.8	10.0	1.00	4.0e-05	2.5e+04	
100 Å	Horizon wavelength	65	151.8	9.9	10.0	1.00	3.0e-05	3.4e+04	
(123.64)	eV	80	152.6	9.9	10.0	1.00	1.4e-05	7.2e+04	
		90	153.2	10.0	10.0	1.00	6.3e-06	1.6e+05	
G3									
200	• lines/mm	65	151.8	9.9	10.0	1.00	1.6e-04	6.4e+03	
	Blaze Wavelength	73	152.2	9.9	10.0	1.00	1.3e-04	7.5e+03	
1.1	(deg) Blaze Angle	92	153.3	10.0	10.0	1.00	9.5e-05	1.0e+04	
	Optical Coating:	100	153.7	10.0	10.0	1.00	8.4e-05	1.2e+04	
2.8	• At. Number	120	154.8	10.1	10.1	1.00	6.1e-05	1.6e+04	
Nickel	Material	140	155.9	10.1	10.1	1.00	4.4e-05	2.2e+04	
251 Å	Horizon wavelength	160	157.0	10.2	10.2	1.00	3.2e-05	3.1e+04	
(49.46)	eV	190	158.7	10.3	10.3	1.00	1.8e-05	5.5e+04	
		220	160.3	10.4	10.4	1.00	8.1e-06	1.2e+05	

Table 5-3b. (continued)

U 5.0 Beam Line 1.0 deg. M1 & M2 2.87 deg. SGM										
Grating Parameters	Photon Wavelength [Å]	Resolved Bandwidth ratio (actual/0.1%)	Grating Illuminated width [mm]	Monit. Aperture (Å)	Source Entrance (Em) [mm, rad]	Flux Fraction Accepted (A)/(Em)	Photon Energy [eV]	Resolved Flux Out Photons/sec Δλ/Δν		
G1 * lines/mm Blaze Wavelength: 1.1 (deg) Blaze Angle Optical Coating: 79 * At. Number GdAl Material 46 Å Horizon wavelength (272.01) eV	12	0.1502	39.5	3.57e-08	7.82e-09	1.00	1033.2	8.12E+11		
	15	0.1095	45.9	3.25e-08	8.30e-09	1.00	826.6	6.40E+12		
	17	0.0904	50.9	3.04e-08	8.60e-09	1.00	729.3	9.83E+12		
	20	0.0689	59.6	2.73e-08	9.04e-09	1.00	619.9	1.16E+13		
	22	0.0578	66.7	2.52e-08	9.32e-09	1.00	563.6	1.11E+13		
	25	0.0444	79.6	2.20e-08	9.72e-09	1.00	495.9	9.24E+12		
	28	0.0339	96.9	1.88e-08	1.01e-08	1.00	442.8	7.31E+12		
	31	0.0254	121.0	1.56e-08	1.05e-08	1.00	400.0	5.52E+12		
	35	0.0164	174.2	1.13e-08	1.10e-08	1.00	354.2	3.37E+12		
	G2 * lines/mm Blaze Wavelength: 1.1 (deg) Blaze Angle Optical Coating: 28 * At. Number GdAl Material 100 Å Horizon wavelength (123.64) eV	26	0.1541	49.2	3.61e-08	9.86e-09	1.00	476.9	3.55E+13	
31		0.1208	56.1	3.37e-08	1.05e-08	1.00	400.0	5.82E+13		
37		0.0927	65.5	3.08e-08	1.12e-08	1.00	335.1	5.96E+13		
42		0.0753	74.6	2.85e-08	1.18e-08	1.00	295.2	5.14E+13		
48		0.0593	87.6	2.56e-08	1.25e-08	1.00	258.3	3.88E+13		
58		0.0398	116.9	2.08e-08	1.35e-08	1.00	213.8	2.84E+13		
65		0.0297	146.8	1.74e-08	1.42e-08	1.00	190.7	1.95E+13		
80		0.0140	180.0	1.11e-08	1.56e-08	0.65	155.0	5.24E+12		
90		0.0063	180.0	5.12e-09	1.65e-08	0.31	137.8	9.80E+11		
G3 * lines/mm Blaze Wavelength: 1.1 (deg) Blaze Angle Optical Coating: 28 * At. Number GdAl Material 251 Å Horizon wavelength (49.46) eV		65	0.1564	69.8	3.66e-08	1.42e-08	1.00	190.7	9.76E+13	
	73	0.1337	76.6	3.51e-08	1.49e-08	1.00	169.8	1.42E+14		
	92	0.0954	94.8	3.16e-08	1.66e-08	1.00	134.8	1.57E+14		
	100	0.0836	103.6	3.01e-08	1.73e-08	1.00	124.0	1.39E+14		
	120	0.0609	129.6	2.63e-08	1.89e-08	1.00	103.3	9.05E+13		
	140	0.0445	164.1	2.24e-08	2.04e-08	1.00	88.6	5.40E+13		
	160	0.0321	180.0	1.85e-08	2.19e-08	0.85	77.5	2.65E+13		
	190	0.0183	180.0	1.25e-08	2.40e-08	0.52	65.3	6.62E+12		
	220	0.0081	180.0	6.39e-09	2.59e-08	0.25	56.4	1.10E+12		

Table 5-3c.

U 3.9 Beam Line		Synchrotron Radiation Source:		Spherical Grating Monochromator:					
2.0 deg. SGM		U	• Source Type (U, W, or "BM")	2.00	• deg. SGM				
		3.90	• Period Length [cm]	176.00	• Included Angle (2θ) [deg.]				
		123	• Number of Periods	• 1	• Diffracted order (m)				
		4.80	• Source Length [m]	1.000	• Magnification of Condensing Mirror System				
Grating Parameters	Photon Wavelength	Photon Energy	Source Flux	Undulator Harmonic	M1 Mirror Reflectance	M2 Mirror Reflectance	Transmitted Flux	Length from	
	[Å]	[eV]	phot/sec 0.1% bw	n			photons/sec 0.1% bw	Entr. Slit to Grating (r)	
								[m]	
G1		12	1033.2	8.32E+14	3	1.000	1.000	8.32e+14	16.00
600	• lines/mm	15	826.6	1.66E+15	3	1.000	1.000	1.66e+15	16.00
Blaze Wavelength		18	688.8	2.31E+15	3	1.000	1.000	2.31e+15	16.00
0.9	(deg) Blaze Angle	22	563.6	2.91E+15	3	1.000	1.000	2.91e+15	16.00
Optical Coating:		26	476.9	1.71E+15	1	1.000	1.000	1.71e+15	16.00
79	• At. Number	28	442.8	2.44E+15	1	1.000	1.000	2.44e+15	16.00
Gold	Material	30	413.3	3.03E+15	1	1.000	1.000	3.03e+15	16.00
41 Å	Horizon wavelength	34	364.7	3.90E+15	1	1.000	1.000	3.90e+15	16.00
(305.39)	eV	38	326.3	4.50E+15	1	1.000	1.000	4.50e+15	16.00
G2		18	688.8	2.31E+15	3	1.000	1.000	2.31e+15	16.00
300	• lines/mm	22	563.6	2.91E+15	3	1.000	1.000	2.91e+15	16.00
Blaze Wavelength		26	476.9	1.71E+15	1	1.000	1.000	1.71e+15	16.00
0.6	(deg) Blaze Angle	30	413.3	3.03E+15	1	1.000	1.000	3.03e+15	16.00
Optical Coating:		36	344.4	4.23E+15	1	1.000	1.000	4.23e+15	16.00
79	• At. Number	42	295.2	4.94E+15	1	1.000	1.000	4.94e+15	16.00
Gold	Material	48	258.3	5.40E+15	1	1.000	1.000	5.40e+15	16.00
81 Å	Horizon wavelength	58	213.8	5.86E+15	1	1.000	1.000	5.86e+15	16.00
(152.69)	eV	70	177.1	6.17E+15	1	1.000	1.000	6.17e+15	16.00

Table 5-3c. (continued)

U 3.9 Beam Line		Gratings:		180 • Grating Width [mm] B • Blazed [B] or Lamella [L] gratings V • Fixed [F] or Variable [V] slit width (variable slit is matched to the diffraction limited image of the source.) 10 • Slit width (if Fixed), or Minimum slit width (if Variable).				
2.0 deg. SGM								
Grating Parameters	Photon Wavelength (Å)	Grating Diffraction Ang's		Grating Reflectance R	*On-blaze* efficiency factor	Diffraction Efficiency/R	Absolute Diffraction Efficiency	
		β (normal)	α (normal)					
		(deg)	(deg)					
-								
G1		12	-88.5910	87.4090	0.224	0.386	0.4054	0.0350
600	• lines/mm	15	-88.7388	87.2612	0.268	0.386	0.8753	0.0907
Blaze Wavelength		18	-88.8866	87.1134	0.285	0.386	1.0000	0.1099
0.9	(deg) Blaze Angle	22	-89.0836	86.9164	0.289	0.386	0.8957	0.0999
Optical Coating:		26	-89.2807	86.7193	0.289	0.386	0.7246	0.0809
79	• At. Number	28	-89.3792	86.6208	0.294	0.386	0.6445	0.0732
Gold	Material	30	-89.4777	86.5223	0.305	0.386	0.5724	0.0673
41 Å	Horizon wavelength	34	-89.6748	86.3252	0.312	0.386	0.4533	0.0546
(305.39)	eV	38	-89.8719	86.1281	0.321	0.386	0.3629	0.0450
-								
G2		18	-88.4433	87.5567	0.393	0.515	0.4975	0.1006
300	• lines/mm	22	-88.5418	87.4582	0.397	0.515	0.8959	0.1830
Blaze Wavelength		26	-88.6403	87.3597	0.401	0.515	1.0000	0.2064
0.6	(deg) Blaze Angle	30	-88.7388	87.2612	0.421	0.515	0.9428	0.2044
Optical Coating:		36	-88.8866	87.1134	0.440	0.515	0.7704	0.1747
79	• At. Number	42	-89.0344	86.9656	0.462	0.515	0.6048	0.1441
Gold	Material	48	-89.1821	86.8179	0.475	0.515	0.4739	0.1159
81 Å	Horizon wavelength	58	-89.4285	86.5715	0.494	0.515	0.3239	0.0825
(152.69)	eV	70	-89.7241	86.2759	0.589	0.515	0.2166	0.0657

Table 5-3c. (continued)

U 3.9 Beam Line 2.0 deg. SGM		Condensing Mirrors:		M1	M2	<div>• Mirror Grazing Incidence Angle (deg.) (Use 0.0 deg. angle if there is no mirror)</div> <div>• Mirror Coating Mat'l Atomic Number</div> <div>• Mirror Coating Mat'l Name</div>			
				0.00	0.00				
				79 Gold	79 Gold				
Grating Parameters		Photon Wavelength	Diff. Limited Source FWHM	FWHM Image Size at	Entrance Slit Width	Slit Flux Transmission	Slit Width Limited	Fractional Bandwidth	Resolving Power
		[Å]	(microns)	Entr. Slit (microns)	Slit Width (vertical) (microns)	Factor (Image/Slit)	$\Delta\lambda_s$ [Å]	$\Delta\lambda_s/\lambda$	$\lambda/\Delta\lambda_s$
G1		12	148.7	148.7	148.7	1.00	0.0070	5.8e-04	1.7e+03
600	• lines/mm	15	148.9	148.9	148.9	1.00	0.0074	4.9e-04	2.0e+03
Blaze Wavelength		18	149.1	149.1	149.1	1.00	0.0078	4.3e-04	2.3e+03
0.9	(deg) Blaze Angle	22	149.3	149.3	149.3	1.00	0.0084	3.8e-04	2.6e+03
Optical Coating:		26	149.5	149.5	149.5	1.00	0.0089	3.4e-04	2.9e+03
79	• At. Number	28	149.6	149.6	149.6	1.00	0.0092	3.3e-04	3.0e+03
Gold	Material	30	149.7	149.7	149.7	1.00	0.0095	3.2e-04	3.2e+03
41 Å	Horizon wavelength	34	150.0	150.0	150.0	1.00	0.0100	2.9e-04	3.4e+03
(305.39)	eV	38	150.2	150.2	150.2	1.00	0.0106	2.8e-04	3.6e+03
G2		18	149.1	149.1	149.1	1.00	0.0132	7.4e-04	1.4e+03
300	• lines/mm	22	149.3	149.3	149.3	1.00	0.0138	6.3e-04	1.6e+03
Blaze Wavelength		26	149.5	149.5	149.5	1.00	0.0143	5.5e-04	1.8e+03
0.6	(deg) Blaze Angle	30	149.7	149.7	149.7	1.00	0.0149	5.0e-04	2.0e+03
Optical Coating:		36	150.1	150.1	150.1	1.00	0.0157	4.4e-04	2.3e+03
79	• At. Number	42	150.4	150.4	150.4	1.00	0.0166	3.9e-04	2.5e+03
Gold	Material	48	150.7	150.7	150.7	1.00	0.0174	3.6e-04	2.8e+03
81 Å	Horizon wavelength	58	151.3	151.3	151.3	1.00	0.0189	3.3e-04	3.1e+03
(152.69)	eV	70	152.0	152.0	152.0	1.00	0.0206	2.9e-04	3.4e+03

Table 5-3c. (continued)

U 3.9 Beam Line								
2.0 deg. SGM								
Grating Parameters	Photon Wavelength [Å]	Resolved Bandwidth ratio (actual/0.1%)	Grating Illuminated width [mm]	Mon'r Acceptance (A) [m. rad]	Source Emittance (Emt) [m. rad]	Flux Fraction Accepted (A)/(Emt)	Photon Energy [eV]	Resolved Flux Out Photons/sec $\Delta\lambda/\lambda$ bw
G1								
600	12	0.5836	18.7	7.56e-08	7.86e-09	1.00	1033.2	1.70E+13
• lines/mm	15	0.4941	18.8	8.00e-08	8.34e-09	1.00	826.6	7.44E+13
Blaze Wavelength	18	0.4344	18.8	8.45e-08	8.80e-09	1.00	688.8	1.10E+14
0.9 (deg) Blaze Angle	22	0.3802	18.7	9.03e-08	9.38e-09	1.00	563.6	1.10E+14
Optical Coating:	26	0.3428	18.6	9.63e-08	9.93e-09	1.00	476.9	4.74E+13
• At. Number	28	0.3281	18.5	9.92e-08	1.02e-08	1.00	442.8	5.66E+13
Gold Material	30	0.3154	18.4	1.02e-07	1.04e-08	1.00	413.3	6.42E+13
41 Å Horizon wavelength	34	0.2945	18.2	1.08e-07	1.09e-08	1.00	364.7	6.27E+13
(305.39) eV	38	0.2780	18.0	1.14e-07	1.14e-08	1.00	326.3	5.63E+13
G2								
300	18	0.7355	22.2	7.15e-08	8.80e-09	1.00	688.8	1.71E+14
• lines/mm	22	0.6270	22.7	7.45e-08	9.38e-09	1.00	563.6	3.33E+14
Blaze Wavelength	26	0.5519	23.1	7.75e-08	9.93e-09	1.00	476.9	1.95E+14
0.6 (deg) Blaze Angle	30	0.4969	23.4	8.05e-08	1.04e-08	1.00	413.3	3.07E+14
Optical Coating:	36	0.4374	23.7	8.50e-08	1.12e-08	1.00	344.4	3.23E+14
• At. Number	42	0.3949	23.9	8.96e-08	1.19e-08	1.00	295.2	2.81E+14
Gold Material	48	0.3632	24.0	9.41e-08	1.26e-08	1.00	258.3	2.27E+14
81 Å Horizon wavelength	58	0.3250	24.1	1.02e-07	1.36e-08	1.00	213.8	1.57E+14
(152.69) eV	70	0.2938	24.0	1.11e-07	1.48e-08	1.00	177.1	1.19E+14

Table 5-3c. (continued)

U 3.9 Beam Line		Spatially Coherent Flux (Half-the-Airy-Disc Coherence Criterion):						
2.0 deg. SGM								
Photon Wavelength		Vert. Source	Horiz. Source	(1/22λ) ²	Flux	Photon	Spatially	
Parameters		Emitance	Emitance		Fraction	Energy	Coherent	
		(Emt)	(Emt)		Accepted	[eV]	Resolved	
		[Å]	[m. rad]	[m. rad]			Flux Out	
							Photons/sec	
							Δλ/λ bw	
G1		12	7.86E-09	6.18E-08	2.14E-18	0.004	1033.2	7.49E+10
600	• lines/mm	15	8.34E-09	6.35E-08	3.35E-18	0.006	826.6	4.71E+11
Blaze Wavelength		18	8.80E-09	6.51E-08	4.82E-18	0.008	688.8	9.28E+11
0.9	(deg) Blaze Angle	22	9.38E-09	6.72E-08	7.20E-18	0.011	563.6	1.26E+12
Optical Coating:		26	9.93E-09	6.92E-08	1.01E-17	0.015	476.9	6.94E+11
79	• At. Number	28	1.02E-08	7.02E-08	1.17E-17	0.016	442.8	9.56E+11
Gold	Material	30	1.04E-08	7.12E-08	1.34E-17	0.018	413.3	1.16E+12
41 Å	Horizon wavelength	34	1.09E-08	7.31E-08	1.72E-17	0.021	364.7	1.35E+12
(305.39)	eV	38	1.14E-08	7.50E-08	2.15E-17	0.025	326.3	1.41E+12
G2		18	8.80E-09	6.51E-08	4.82E-18	0.008	688.8	1.44E+12
300	• lines/mm	22	9.38E-09	6.72E-08	7.20E-18	0.011	563.6	3.81E+12
Blaze Wavelength		26	9.93E-09	6.92E-08	1.01E-17	0.015	476.9	2.85E+12
0.6	(deg) Blaze Angle	30	1.04E-08	7.12E-08	1.34E-17	0.018	413.3	5.54E+12
Optical Coating:		36	1.12E-08	7.41E-08	1.93E-17	0.023	344.4	7.52E+12
79	• At. Number	42	1.19E-08	7.68E-08	2.63E-17	0.029	295.2	8.08E+12
Gold	Material	48	1.26E-08	7.95E-08	3.43E-17	0.034	258.3	7.81E+12
81 Å	Horizon wavelength	58	1.36E-08	8.38E-08	5.01E-17	0.044	213.9	6.90E+12
(152.69)	eV	70	1.48E-08	8.86E-08	7.29E-17	0.056	177.1	6.63E+12

5.3.1 The Rense and Violett Spherical-Grating Monochromator System. As discussed in Section 5-1, the spherical grating is capable of excellent resolution and meets the needs of beam-line applications, provided a way can be found to correct the astigmatism. This is necessary if we are to achieve a final image that is nominally a point rather than a line. Rense and Violett's [1959] approach to this is to use a condensing system that images the source onto the entrance slit in the dispersion (vertical) plane and images the source onto the exit slit in the horizontal plane (see Fig. 5-2). Thus, the astigmatism of the grating is canceled by that of the condenser, and the final image is stigmatic to first order. The effect on the resolution of this method of illuminating the grating can be explored by analytical studies and by exact computer ray tracing. Both methods show that, for the large grating radii of interest to us, the resolution is not compromised.

The optical principles underlying the three beam lines are the same. The application to different wavelength regions is accommodated by different choices of grazing angle. The 2.87° -grazing-angle instrument is of the same design as one constructed at LBL for use on the LBL/Exxon/SSRL 54-pole wiggler beam line at Stanford. The grating rotation axis and the ingoing and outgoing ray directions are fixed. Wavelength tuning is by simple rotation of the grating. Good focus is preserved throughout the scanning range by sliding the exit slit along the beam direction. The Rowland-circle condition can be satisfied exactly over part of the range, and approximately over all of it, by combined motion of both slits. The motion of the slits over a certain range is within the depth of focus of the condenser and the depth of field of the refocusing mirror. Exact accommodation to the slit location can be achieved by very slight elastic deformation of the mirrors.

Fig. 5-2. Schematic diagram of the Rense and Violett spherical-grating monochromator system. The condensing mirrors M1 and M2 are designed so that M1 focuses in the horizontal plane to the exit slit, and M2 focuses in the vertical plane to the entrance slit. Each mirror has essentially zero focusing effect in its sagittal direction.

Fig. 5-3. Resolved photon flux from the undulator beam lines of Table 5-2: (a) U8.0, (b) U5.0, and (c) U3.9. The data shown here are for spherical-grating monochromators with 10- μ m slits or slits set to match the diffraction-limited image of the source. Table 5-3 contains quantitative details of the performance of these beamlines. Spatially coherent flux is also shown for U3.9.

Our choice of condensing system stems from our all-spherical philosophy. We choose to use two spherical mirrors with their planes of incidence perpendicular to each other, in the configuration originally used by Kirkpatrick and Baez [1948] except for beam line U3.9, for which no condensing mirrors are used before the monochromator. The parameters of the mirrors and gratings for the three Rense and Violett systems are included in Table 5-2, and the operational parameters are in Table 5-3. The flux is also shown in Fig. 5-3, for the situation in which the monochromators are set for best resolution.

To evaluate these systems properly, we need to be aware of their phase-space acceptance, as well as their resolution, and this is meaningful only in relation to the emittance of the photon beam from the source. In Fig. 5-4, we show the phase-space acceptance of the three monochromators for a 10- μ m slit setting and the corresponding source emittances as a

Fig. 5-4. Plots of the monochromatic photon-beam emittance in the vertical plane for all three undulators and the phase-space acceptance for the proposed monochromators for these sources, assuming 10- μ m slits. The acceptance is defined as the product of the full width and full angular width, and the emittance is defined as the full width at half-maximum of the Gaussian distributed variables. In these units, the electron-beam emittance is 2.35² times larger than in the usual units used elsewhere in this handbook. When the acceptance curve lies above the emittance curve, the entire beam can, in principle, be accepted. When the source is diffraction limited, the slit size is assumed to be matched to the diffraction-limited source image; hence the resolution in this case is diffraction limited.

function of wavelength. This is a typical value for a high-resolution experiment, although it is not the ultimate. To give a more complete picture of the resolution capability of these systems, we show a full plot of the resolution capability of the monochromator (2.87° grazing angle) for beam line U5.0 in Fig. 5-5. This is determined by computer ray traces of rays emerging from a $10\text{-}\mu\text{m}$ entrance slit. We note that very good values are predicted for the resolution and that the entire beam can be accepted by the monochromator in most cases, even at the $10\text{-}\mu\text{m}$ slit width (see Fig. 5-4). This is a consequence of the outstanding phase-space properties of the source.

5.3.2 A Soft X-Ray Crystal Monochromator. There are fewer design options for a crystal monochromator than there are for a grating monochromator operating in the soft x-ray region. If the instrument must have constant deviation, then the design is essentially limited to the two-crystal monochromator, with the crystals in the antiparallel position. This type of instrument has been implemented at a number of synchrotron radiation facilities.

Fig. 5-5. Representative plots of the resolution of the 2.87° spherical-grating monochromator of beam line U5.0. The plots are for $10\text{-}\mu\text{m}$ slits and are derived from computer ray traces of the whole beam line. The solid lines correspond to regions where the Rowland condition is exactly satisfied and where resolution is slit-width limited. The dotted lines correspond to regions where the Rowland condition is only approximately satisfied and where the resolution is aberration limited.

The monochromator should ideally operate in parallel light to give the highest resolution. However, since the natural deviation of the x-rays is already small in the vertical direction, we use a vertically deflecting mirror to magnify the source and improve the collimation so that the spectrometer can work in weakly convergent light without impairing its natural resolution. This mirror is again spherical, so an additional mirror, crossed with the first in the Kirkpatrick-Baez configuration, is required for horizontal collection. Both these mirrors are inside the shielding walls. The vertically deflecting mirror is 9.4 m from the source and focuses at a distance of 18.8 m for a magnification of 2.0. The horizontally deflecting mirror is at 10.4 m, yielding a magnification of 1.7.

If the crystals were subjected to the full intensity of the wiggler radiation, even after it had been reflected and filtered by the two mirrors, they would suffer various unwanted changes in their optical properties, particularly in their lattice spacing. The calibration and efficiency of the instrument would consequently change. In addition, some sensitive crystals might be permanently degraded by radiation damage. It is therefore imperative to find some method for reducing the heat and radiation load on the crystals. We have proposed to do this by using a pre-monochromator, similar in principle to the main monochromator, except that the two elements will be artificially fabricated multilayer structures, rather than natural crystals. These devices are generally made of refractory elements such as tungsten and carbon or molybdenum and silicon and can be deposited on massive polished metal substrates that can be water cooled. The power density is lower than that on a natural crystal, because the $2d$ spacings are larger and thus the incidence angles are more grazing. Furthermore, the large angular width of the Bragg peak of multilayers implies that the pre-monochromator will not be detuned by small changes in the lattice spacing. Although this is a fairly new concept, experimental results and detailed design studies indicate that the

Fig. 5-6. Photon flux from a double-crystal monochromator, for two crystals, in conjunction with wiggler W13.6. More detailed parameters appear in Table 5-2.

Fig. 5-7. Photon-beam emittance in the vertical plane for the wiggler beam line, together with the phase-space acceptance of the crystal monochromator, for two crystals, beryl and germanium (111), which are assumed to be 25 mm wide. The numbers at the endpoints of the curves are realistic estimates of the resolution (in eV), based on both the rocking-curve width and the degree of collimation of the beam. The latter is based on acceptance of everything inside the full width at half maximum.

multilayer pre-monochromator approach offers the most satisfactory method of monochromator crystal protection. Both the pre-monochromator and the main monochromator are ultrahigh-vacuum devices.

The parameters for this beam line are shown in Table 5-2. The flux from the monochromator is shown in Fig. 5-6. The phase-space acceptance of this system has also been calculated and is shown in Fig. 5-7, relative to the emittance of the photon beams emerging from the wiggler and a bending magnet.

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