Synchrotron radiation research—

An incisive research tool is shedding new light on difficult problems in fields ranging from biology to physics, prompting a major expansion of source facilities.

Arthur Bienenstock and Herman Winick

Synchrotron radiation, with its remarkable properties and eminent suitability for scientific and technical applications, is having a profound effect on the many disciplines that make use of radiation in the x-ray and vacuum ultraviolet regions of the spectrum. Indeed, the rapidly increasing availability of this radiation is revolutionizing some fields and is leading to a variety of new interdisciplinary collaborations. Seeking to take advantage of this incisive tool, scientists around the world are requesting time at synchrotron radiation facilities in such large numbers that the fast-paced construction of new sources—including several in less-developed countries—has yet to bring the level of availability up to that of demand.

In May 1981, PHYSICS TODAY devoted a special issue to synchrotron radiation research. Four articles[1] reviewed facilities, applications and the then newly developed wiggler and undulator sources. In the intervening two years there have been very significant changes in the nature and availability of synchrotron radiation sources. Five new facilities have begun operation, and a similar number of facilities already in operation have undergone major expansions. The nature of synchrotron radiation research has also changed significantly, as have our expectations. Consequently, PHYSICS TODAY will publish a series of articles describing these changes in detail.

In this first article we will cover a number of topics:

- ▶ the expanding user community that is seeking access to synchrotron radiation sources
- ▶ recent research results that illustrate the benefit of higher flux and brightness
- ▶ properties and sources of synchrotron radiation
- ▶ permanent-magnet technology and its impact on synchrotron radiation research
- ▶ factors that limit the power density of synchrotron radiation
- ▶ present and future synchrotron radiation research facilities.

Future articles in this series will present more detailed descriptions of the latest developments in specific research areas. Several comprehensive reviews[2–4] of synchrotron radiation research and past accomplishments are also available.

The user community

As might be expected in a rapidly developing field, the number of scientific participants is increasing rapidly. This increase was documented recently in the report[5] of a National Academy of Sciences committee that studied the current status of facilities dedicated to the production of synchrotron radiation. (See PHYSICS TODAY, February, page 21.) The committee, chaired by Iowa State University physicist David W. Lynch, found that the number of users of such facilities in the United States has grown from approximately 210 in 1976 to about 350 in 1980 and to about 600 in 1982.

As the report shows, this growth is limited by the availability of facilities, rather than by the number of scientists who want to perform synchrotron radiation experiments. A recent survey by operators of the National Synchrotron Light Source at Brookhaven National Laboratory in New York, specifically designed to assess general user demand, indicated that approximately 1000 scientists are interested in using the facility, 70 percent of whom have not previously used synchrotron radiation. Similarly, time at the Stanford Synchrotron Radiation Laboratory remains oversubscribed by a factor of two to three, in spite of the development of new experimental stations and considerable dedicated time. When we take into account the pace at which experimental stations are being developed at all facilities, it appears as if there will be no time in the forseeable future in which the supply of experimental stations will come close to meeting the demand.

One feature of the user community that the Lynch committee did not discuss is well worth noting—its heterogeneity. Users of synchrotron radiation facilities come from the fields of applied physics, biology, biochemistry, biophysics, chemical engineering, chemistry, electrical engineering, geology, materials science, medicine, metallurgy and physics. Because each synchrotron radiation laboratory has many experimental stations, it is common to find scientists from different disciplines working near each other on related experiments. This proximity has led to a rapid spread of ideas and techniques among the disciplines, and it has allowed interdisciplinary collaborations to grow from recognized advantages to the scientists, rather than from administrative decisions.

The nature of the synchrotron radiation laboratories also has an unusual effect on graduate education. Because of the above-mentioned proximity, graduate students working at the laboratories frequently get to know and to work with senior scientists from institutions other than their own. As a result, they gain experience that cannot be obtained from a single thesis supervisor. The many synchrotron radiation publications involving a graduate student and a senior scientist from an industrial laboratory are evidence of these unusual circumstances.

On the other hand, the extreme

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an overview

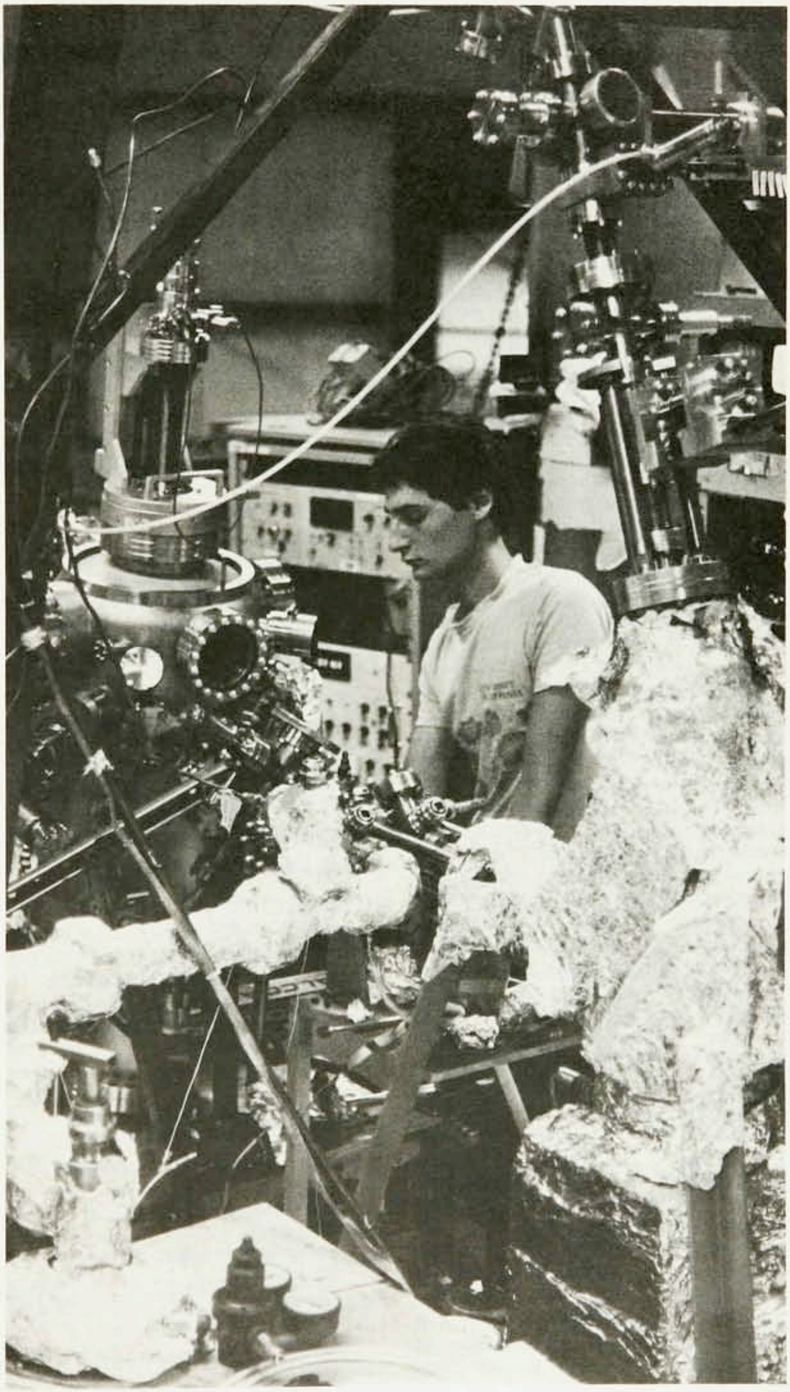
demand for beam time does not allow for the graduate students' learning by correction of errors, which is so effective in the more common bench-top science. There is little tolerance of wasted beam time in most laboratories.

New developments

As the box on page 50 indicates, the range of synchrotron radiation research is so broad that it cannot be covered in a single article. There is, however, one theme that unifies much of it, namely, that synchrotron radiation has increased vastly our ability to determine electronic states and atomic arrangements in complex systems and in systems with very low rates of interaction with electromagnetic radiation. (See figure 1.) This new capability comes at a time when much attention in condensed-matter science is being turned to systems and phenomena such as amorphous materials, organic conductors, dirty superconductors, interfaces, phase transitions in various dimensions and the microscopic level of biological function.

With the expansion in the number of facilities, the increase in the number of users, and the improvement of sources, new research developments using synchrotron radiation have come rapidly.

EXAFS. Extended x-ray absorption fine-structure analysis was one of the first new techniques to fluorish as a result of synchrotron radiation.[6] In this technique, one measures the x-ray absorption coefficient as a function of photon energy in the region from just below to approximately 1000 eV above the K- or L-absorption edges of a specific element in a polyatomic material. The absorption coefficient is directly linked to the probability of exciting the electron from the K- or L-shell to the continuum. Above the edge, the absorption coefficient exhibits a fine structure from which one can deter-



Photoemission experiment using synchrotron radiation, operated by Stanford graduate student Joel Silberman. The beam descends from a mirror situated above the apparatus pictured here; it enters a Seya-Hamioka monochrometer and then goes into the ultra-high-vacuum chamber at the left, where it encounters the sample. The aluminum foil distributes heat during bakeout of the equipment. The vacuum is better than 10^{-10} Torr. (Photograph by Chuck Painter, Stanford Linear Accelerator Center.) Figure 1 mine the average coordination of that species by its neighbors. That is, one can determine the distances to nearest and, in some cases, more distant neighbors, the mean square deviations of those distances, the number of neighbors and, often, the atomic species of neighbors. Such information is increasing our understanding at an atomic level of the functioning of metalloproteins and metalloenzymes, as well as dilute constituents in both crystalline and amorphous materials.

The EXAFS technique, in its simplest form, was well suited to the initial mode of most x-ray synchrotron radiation work, as "parasitic" on high-energy-physics facilities. For constituents present at atomic concentrations of 5 percent or more, the EXAFS data for a specific edge could be gathered in minutes. Investigators soon recognized, however, that *any* process directly linked to the excitation of electrons shows fine structure as a function of photon energy. This led rapidly to the development of new techniques for the analysis of atomic arrangements, and these new methods, in turn, require higher photon fluxes.

The first of these methods was fluorescence analysis. With the absorption technique, the constituent whose coordination we wish to determine must be present in concentrations sufficiently high to make an appreciable contribution to the total absorption. If that contribution is too small, then we cannot see the fine structure because the effective signal-to-noise ratio is too low. We can effect a tremendous increase in that ratio, however, by measuring the intensity of K- or L-fluorescence from the element of interest, because the contribution of the other constituents to that fluorescence is negligible. Using this fluorescence technique, experiments are readily determining the coordinations of constituents present at concentrations of one part in 10^5. As a result, EXAFS analysis has become even more important for studying metalloproteins at biologically important concentrations and impurities in a wide range of systems.

It is important to note, however, that while the fluorescence technique does increase the signal-to-noise ratio, in dilute systems the effective event rate is decreased by orders of magnitude because of the small number of fluorescing atoms. As a result, more flux is required to allow the performance of the experiment in a reasonable amount of time.

The need for increased flux became even more evident with the development of surface EXAFS. In this approach, one determines the coordination of a layer of atoms on the surface of a material through measurement and analysis of the yield of Auger electrons as a function of photon energy above the absorption edge. Because Auger electrons are emitted following the excitation of the K- or L-shell electrons, the yield must show the fine structure. And because most Auger electrons have very short mean free paths, those that reach the detector originate very close to the surface. Thus, the Auger yield provides a means for determining the coordination of individual atomic species on the surfaces of both crystalline and amorphous materials. However, the total number of surface atoms is small and the Auger electron yield per absorbed photon is frequently less than unity; the experiment, therefore, requires high flux if it is to be performed in a reasonable amount of time. Here, "reasonable" is often determined by the amount of time that one can maintain the sample surface in the appropriate state.

Even greater specificity in surface studies comes from the study of EXAFS through the phenomenon of photon induced desorption. Among the most interesting utilizations of this phenomenon is in the situation in which a substrate of element A is partially covered by element B. In some cases, when photons with energy just above the absorption edge of an A-atom impinge on the surface and lead to Auger emission by A atoms, atoms of species B adjacent to the emitting A atoms are desorbed. Thus, in spite of the fact that most of the A atoms are not adjacent to B atoms, by measuring B-atom desorption as a function of photon energy, one can determine the coordinations of those A atoms that are adjacent to B atoms. As before, the technique is applicable to the surfaces of amorphous

Types of synchrotron radiation studies

Photoemission
- Energy resolved
- Angle resolved
- Energy and angle resolved
- Fundamental physics of photoionization
- Bulk electronic states
- Surface electronic states
- Interface phenomena

Photoelectron diffraction
- Surface atomic arrangement determination

Time-resolved fluorescence spectroscopy
- Semiconductor electron–hole recombination
- Molecular rearrangements on protein chains

Soft x-ray lithography

Soft x-ray microscopy

Atomic physics
- Deep-shell phenomena
- Compton scattering

X-ray diffraction and scattering
- Small-angle scattering (static and time-resolved)
- Large-angle scattering (static and time-resolved)
- Anomalous scattering
- Surface layers
- Two-dimensional arrays
- Protein crystallography
- Amorphous materials

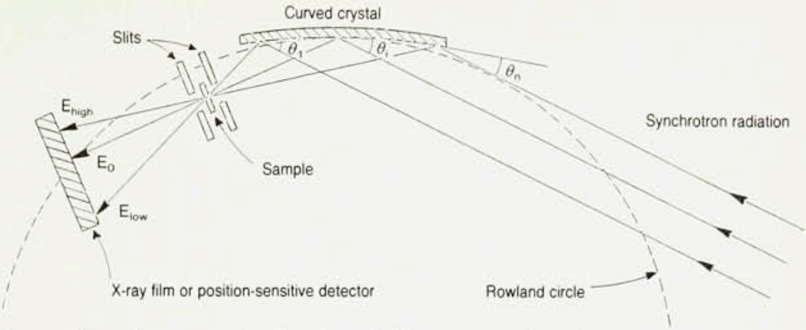
EXAFS and absorption spectroscopy
- Bulk
- Fluorescence
- Surface
- Photon induced desorption
- Time-resolved
- Physics of EXAFS and near-edge phenomena
- Proteins and enzymes
- Impurities
- Amorphous materials

Non-invasive medical radiography (angiography)
- Contrast enhancement by digital subtraction of images above and below an absorption edge

X-ray fluorescence analysis
- Detection of very dilute species

as well as crystalline materials, and again, it is quite a photon-hungry approach.

Still another photon-hungry approach to EXAFS analysis is the energy-dispersive method, in which one places the sample in a convergent, white x-ray beam. As figure 2 shows, the quasiparallel x-ray beam impinges on a curved crystal. Because of the curvature, the glancing angle of the beam varies continuously across the crystal surface and results in different x-ray wavelengths being reflected from different points of the crystal surface. These pass through slits and come to a focus at the location of the sample. They then diverge and impinge on a position-sensitive detector or x-ray film, with position corresponding to photon energy. Such a system allows for the measurement of an absorption EXAFS pattern in a time determined by the total incident flux and the detector speed; hence the desire for higher flux. This approach offers the opportunity to follow changes in atomic arrangements as materials and biological systems undergo structural transformation or chemical changes. That is, it offers the opportunity to observe the dynamic structural changes that accompany kinetic phenomena. Such studies should lead to significant advances in our understanding of the kinetics of complex systems at an atomic level.



Energy-dispersive EXAFS. In this schematic diagram, a quasiparallel x-ray beam meets the surface of a crystal at a continuum of angles because the surface is curved. Different angles of incidence favor the reflection of different energies. (From reference 21.) Figure 2

Diffraction and scattering techniques using x rays from synchrotron radiation have undergone extensive development, which has also resulted in a need for more facilities and greater intensities. This need is largely the result of new experimental approaches, which were not anticipated when present synchrotron radiation sources were planned.

For example, an unexpected aspect of radiation damage to protein crystals has led to the extensive use of synchrotron radiation for the high real-space resolution of their structure. In general, the volume in reciprocal (wavevector) space in which one can obtain data from protein crystals using normal x-ray generators is restricted by radiation damage to the protein crystal. One would expect that the higher intensities of synchrotron radiation would just increase the rate of radiation damage and lead to the same accessible volume in reciprocal space and thus the same resolution. It turned out, however, that radiation damage to protein crystals is not proportional to the integrated radiation dose alone, but to the time over which the protein is exposed to the radiation, as well. Thus, one can obtain more data at the high intensities available with synchrotron radiation than one can obtain with the lower-level radiation from an x-ray tube.[7] As a result, many synchrotron radiation facilities are constructing more stations where experimenters can obtain simple film data on protein crystals from greater volumes in reciprocal space and, therefore, higher real-space resolution. Thus, an unexpected effect has led to more extensive use of synchrotron radiation than was anticipated. Figure 3 shows a schematic layout of a beam line that includes a rotation-camera station for such studies.

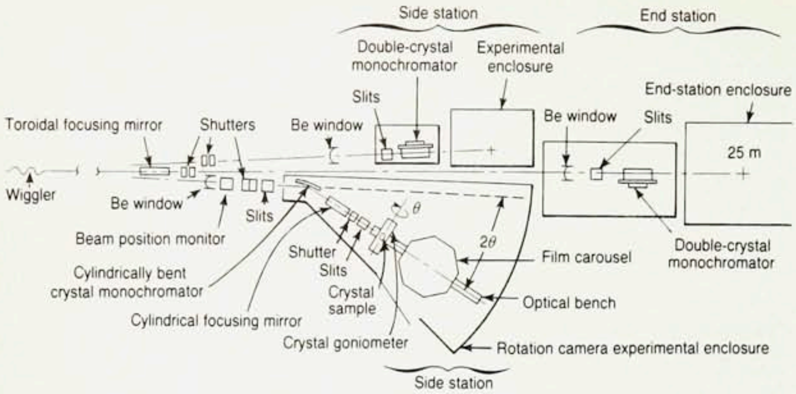
Another unanticipated development involves the anomalous scattering of x rays. At photon energies well separated from any absorption edges in a material, the atomic or ionic x-ray scattering factor is just the Fourier transform of the electron density. When the photon energy is close to an absorption edge, however, the atomic scattering factor has real and imaginary shifts associated with resonance. When synchrotron x-ray facilities were being developed, it was apparent that one could use this phenomenon to determine the phases associated with x-ray diffraction from crystalline materials, and that one could also use it to get partial distribution functions in binary amorphous and liquid alloys. In fact, the use of this technique has been less than was anticipated.

On the other hand, a method known as differential anomalous scattering, in which one determines the derivative of the intensity with respect to photon energy, has proved[8] to be of significant value. In particular, this method provides a weighted sum of partial pair distributions involving the atom whose absorption edge is being studied. The resulting information is complementary to that obtained with EXAFS, but shares with EXAFS the characteristic of providing detailed information about the bonding of a particular atomic species in a polyatomic material.

Still another field of structural research that was not anticipated in the early days of synchrotron radiation is the study of two-dimensional atomic arrangements. Using the extremely high intensity available from wigglers, these studies employ two quite different techniques for different situations. Monolayers and thin films on substrates are studied[9] utilizing the total reflection that occurs when the angle between the incident x rays and the surface is less than the critical angle. Under such circumstances, the x rays penetrate quite far—some tens to hundreds of angstroms, depending on the angle of incidence and the optical coefficients. While penetrating those distances, the x rays are diffracted in a manner that allows one to measure the diffraction intensities and analyze them to determine atomic arrangements. This technique was even used recently to study atomic arrangements in a thin amorphous layer. Phase transitions in two dimensions—and the changes in the nature of these transitions as the dimensionality increases from two to three—are studied[10] in diffraction experiments on self-supporting liquid-crystal films as well as films on substrates. (See figure 4.) These experiments represent an extreme of demand for high-intensity sources, both because of the small number of atoms involved in the scattering process and because extreme reciprocal-space resolution—and hence high intensity—is required to determine the behavior of the two-particle correlation function as the system's temperature is lowered to the freezing point, where the correlations become very long range.

Also developing rapidly—and requiring increasing source intensities—is the field of time-resolved x-ray scattering. In all experiments in this field, the goal is to determine the change with time of atomic arrangements. Different types of experiments deal with different aspects of those arrangements.

In time-resolved Bragg scattering experiments[11] on a semiconductor surface, for example, laser pulses are synchronized with pulses of synchro-



Multistation wiggler beam line. This layout of a facility at SSRL shows how several branch lines share a fan of radiation from a single wiggler magnet. Figure 3

tron radiation and the x-ray diffraction pattern is measured at specified intervals after the surface is subjected to the laser pulse. These measurements reveal details of the laser annealing process. Experiments have shown, for instance, that laser annealing does involve melting and recrystallization of the surface. (See PHYSICS TODAY, June 1982, page 24.) Because the quality of the data obtained in time-resolved Bragg scattering experiments is limited by the total source intensity, we can anticipate considerable improvements in such studies as sources grow more intense.

In similar time-resolved small-angle scattering experiments on muscles, biophysicists have measured the changes in repeat distances as muscle undergoes cycles of contraction and expansion. In these experiments, as in the Bragg scattering experiments, even synchrotron radiation intensities have been insufficient, so that the scattered intensities have to be averaged over many cycles to yield the required structural data.

More recently, there have been studies[12] of non-cyclic phenomena using time-resolved small-angle x-ray scattering. One experiment, for example, studied in detail the phenomenon of phase separation as a polyatomic amorphous material is quenched from a temperature at which it is homogeneous to a temperature below the miscibility dome. This work utilized a bending-magnet beam line at the Stanford Synchrotron Radiation Laboratory, which made possible a time resolution on the order of 30 seconds when the scattering was weak in the early stages of phase separation.

Photoionization processes. Synchrotron radiation, as we mentioned earlier, has greatly increased our ability to determine the electronic and structural properties of matter on an atomic scale, as well as our understanding of the photoionization processes that are usually the chief interaction of the electromagnetic radiation with the matter. A case in point is photoemission from solids, where the last few years have seen an ever increasing ability to measure energy, momentum and spin with high accuracy. A later article in this series will cover this fast-growing field.

As far as the basic process of photoionization is concerned, it is important to realize that measurements of total absorption using conventional excitation sources have accumulated a vast amount of information over the years. The high intensity and tunability of synchrotron radiation have made it possible to separate out the contributions from the different electronic subshells. That is, we can now measure partial photoionization cross sections and the various processes occurring close to the ionization threshold. These observations relate to the most fundamental questions of electronic ionization: To what extent is a one-electron description sufficiently accurate, and under what circumstances must we consider more complicated interactions?

The most outer, filled subshells of barium have the electronic configuration $4d^{10}5s^25p^6$. With synchrotron radiation, one can tune through the ionization threshold of the 4d electrons while looking to see what happens to the ionization probability of the 5s and 5p electrons. There is a very dramatic enhancement in the emission of 5s and 5p electrons at the ionization threshold of the 4d subshell. This many-electron effect arises because the 4d subshell becomes highly polarized when it loses one electron; the resulting field distortion around the 4d shell is sufficient to drive the emission of electrons from the 5s and 5p subshells.

Experiments of this type require high intensity over a continuous spectral region, and were not feasible before synchrotron radiation was available. Gas-phase photoemission measurements require still higher intensities. To make these measurements, researchers have had to resort to yet another unique feature of synchrotron radiation, namely its pulsed time structure. The time structure of the electron bunch in the SPEAR storage ring is such that one can apply a time-of-flight technique to measure the energy distribution of the photoemitted electrons. Because the entire energy spectrum is collected simultaneously there is a considerable reduction in the data acquisition time. These experimental advances have recently opened the door to a wealth of information about atomic autoionization resonances and the physical processes that underlie these phenomena.

Bending magnets

Synchrotron radiation is the electromagnetic radiation emitted by charged particles undergoing curved motion in magnetic fields. High-energy electron or positron storage rings offer synchrotron radiation that is stable, pulsed, polarized and collimated over a broad photon energy range—from infrared to x ray—usually with an intensity five or more orders of magnitude higher on small experimental samples than is available from other continuum sources.

Because synchrotron radiation is produced copiously in the bending magnets of electron synchrotrons and storage rings, these magnets were quite naturally the first sources to be used for experiments. As figure 5 indicates, bending magnets provide an intense, broad continuum. For electrons of energy E, in a magnetic field B, this continuum is characterized by a critical energy $0.665\,BE^2$ keV/(T Gev^2), beyond which the flux begins to fall. Half the power is radiated above the critical energy. The intensity is generally considered to be useful out to about 4 times the critical energy.

The radiation is emitted into a narrow forward cone (relative to the instantaneous electron direction) with an opening angle given approximately by m_0c^2/E, the ratio of the electron rest mass energy to its total energy. Thus, for electrons of 1 GeV the opening angle of the cone of emitted radiation is only about 1 mrad. At higher electron energies this angle is even smaller, resulting in radiation patterns at distances of 10–30 m from the source point that are confined to only a few millimeters in the direction perpendicular to the plane of deflection of the electron. Because the electron is almost always deflected in a horizontal plane, this small photon-beam dimension is in the vertical direction. The radiation emitted precisely along the instantaneous direction of motion is linearly polarized with its electric vector in the direction of the acceleration. Off this axis the polarization is elliptical.

Because the bending magnets produce a continuous curvature in the electron beam, the angular spread of the synchrotron radiation in the plane of deflection is far greater than the natural emission angle. Each bending magnet thus provides a fan of radiation several degrees wide in the horizontal plane, making possible the installation of several spatially separated experimental stations, each using a different part of the fan from the single bending magnet.

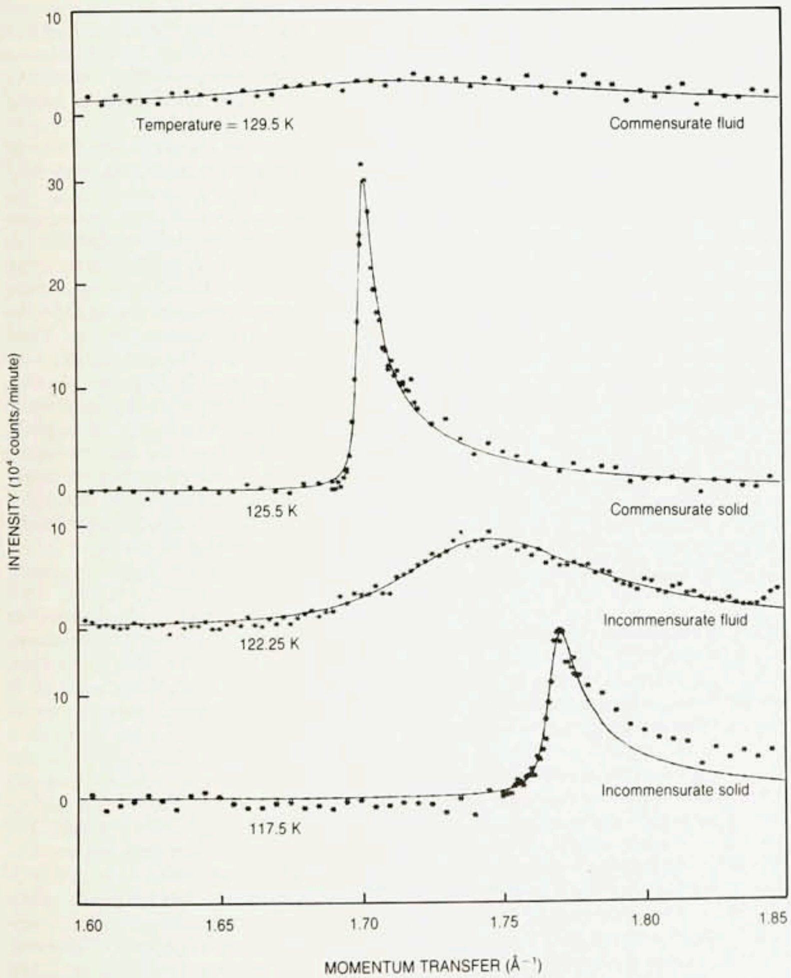
Wiggler magnets can also generate such fans. The schematic diagram in figure 3 shows how several branch lines can operate simultaneously, sharing the radiation from a single wiggler or bending magnet. By contrast, an undulator magnet, as we will explain later, produces an extremely narrow cone of radiation, which can be used by only one station at a time. Figure 6 is a schematic diagram of an undulator beam line with three experimental stations that operate sequentially, using insertable mirrors.

Wigglers and undulators

Experimenters who need synchrotron radiation have made excellent use of the flux from bending magnets, particularly as enhanced with the focusing techniques that we have mentioned. However, as we have seen, many experiments need even higher fluxes, and in some cases higher spectral brightness (flux/steradian for a unit source area, within a small bandwidth) to perform the most difficult experiments, requiring high temporal or energy resolution. It is now clear that wiggler and undulator magnets can provide this higher flux and brightness, as well as extended spectral range. Figure 5 gives a brightness comparison for bending magnets, wigglers and undulators for a proposed new 1.3-GeV, 400-mA ring.

Wiggler and undulator magnets are periodic devices, which one may insert into the straight, field-free sections of electron storage rings. These magnets cause the electrons to curve back and forth, and thus to radiate. The use of wigglers and undulators as sources of radiation began only recently. The first wiggler to serve as a source of synchrotron radiation was a six-pole electromagnet with a peak field of 1.8 T that caused the electron beam to undergo 3 oscillations in 1.2 meters. It went into regular use for experiments at the Stanford Synchrotron Radiation Laboratory in 1979. The first undulator to provide radiation for an experiment was a 60-pole permanent magnet with a peak field of 0.23 T that caused the electron beam to undergo 30 oscillations in 2 meters. That was in late 1981, and also at Stanford. The first wiggler, the first undulator, and other magnets that have now been used at other labs, performed as expected. They produced greatly enhanced radiation and were compatible with the operation of storage rings. But, because most of the new storage rings now coming on line were designed before these successful experiments, they were designed primarily to serve a large number of users with bending-magnet radiation and have only a few spaces to insert wigglers or undulators. To increase the intensity and brightness of the bending-magnet radiation, some of the new rings were designed for large stored current and low electron-beam "emittance" (the product of transverse beam size and divergence).

Because wigglers and undulators provide the highest intensity and brightness, there will be a need for a much larger number of these sources to serve the growing user community and to meet the demands of the most difficult, and often most exciting, experiments. Thus, physicists are now proposing[15–17] sources based exclusively on wigglers and undulators. In these rings the bending magnets serve to circulate the stored beam through a large number of insertion magnets, and



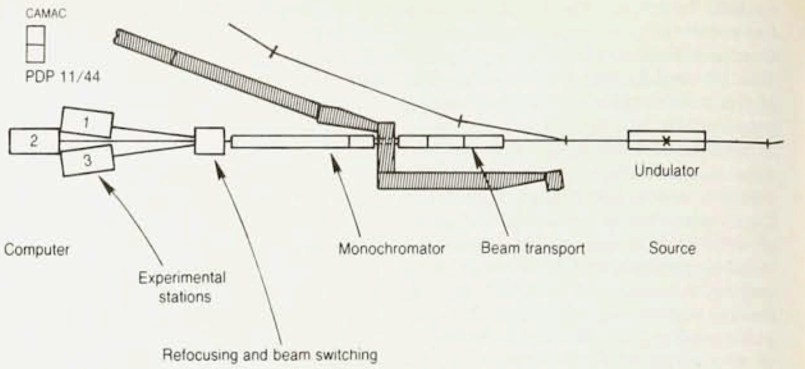
Scattering data for x rays hitting a monolayer of krypton on a graphite substrate. The background from the graphite and krypton gas has been subtracted. As the temperature decreases, the layer evolves from a fluid with correlations extending only as far as 25 Å, to a solid with correlations limited only by the size of the crystals in the substrate. With further cooling the sample melts into a fluid incommensurate with the substrate. The sample finally condenses into a solid phase. The difference in the line shapes between the solid scans at 117.5 K and 125.5 K is connected with the fundamental difference in behavior of systems with continuous and discrete symmetry in two dimensions. These experiments were performed at SSRL by Eliot Specht, Mark Sutton, David Moncton, Paul Horn and Robert Birgeneau. Figure 4 little or no use is made of the radiation produced in the bending magnets themselves. These proposed new rings aim for even lower emittance than any present ring, and they aim to increase brightness, particularly of undulator sources. For the high-energy rings only moderate currents of 0.1 A are proposed, rather than the higher currents that were the goal of earlier rings based on bending magnet sources. This is because intensities from wiggler and undulator magnets will be limited by the difficulty in designing beam-line optical elements that can operate at power densities of over 10 kW/cm^2, which even moderate currents can produce.

Characteristics of radiation. Wiggler and undulator magnets have, therefore, transformed our notions of how a laboratory for synchrotron radiation research should be designed. Because of the importance and proliferation of these magnets, we will describe here some of the important characteristics of the radiation they produce, and refer the interested reader to the more detailed description in the May 1981 issue of PHYSICS TODAY[1] and to more recent reviews.[18,19]

To characterize wigglers and undulators, the dimensionless "undulator parameter" K is very useful:

$$K = (eB_0 \lambda_u)/2\pi m_0 c = 0.934\, B_0 \lambda_u \ \ \mathrm{T^{-1} cm^{-1}}$$

Here B_0 is the peak magnetic field, and



Undulator beam line layout, showing three stations for vacuum ultraviolet and soft-x-ray experimental work. Only one station operates at a time; mirrors deflect radiation to the side stations. The distance from the source to the experimental stations is about 20 meters. Figure 6

λ_u is the period length. When the magnetic field is sinusoidal, the parameter K is $\gamma\delta$, where γ is E/m_0c^2 and 2δ is the full angular excursion of the electron beam traversing the wiggler or undulator magnet. We will restrict our attention to devices with transverse magnetic fields of alternating polarity. These fields cause the electron beam to undergo transverse oscillations that result in linearly polarized radiation, but no net displacement or deflection of the beam. Helical wiggler or undulator magnets, in which the magnetic field is constant in magnitude but rotates in direction, offer circularly polarized radiation but require small circular beam pipes that provide too little aperture for the beam in most present storage rings. It appears possible to design new rings that can accommodate helical magnets.

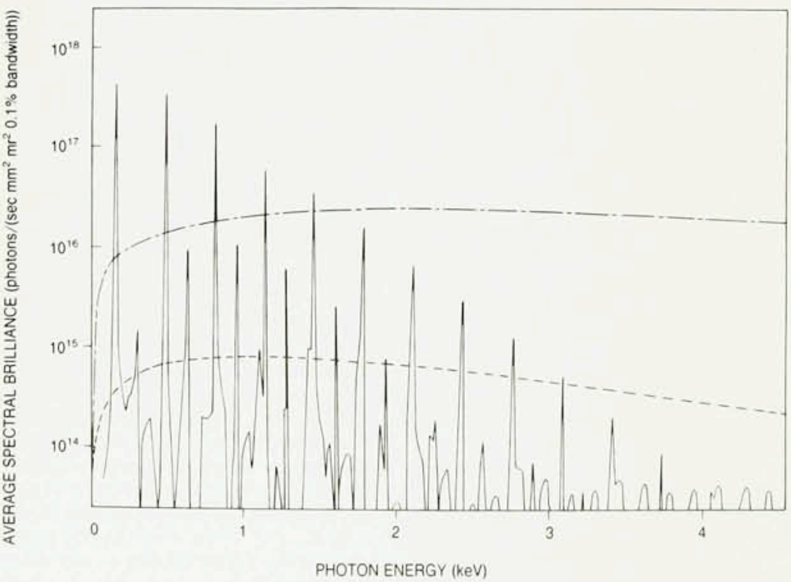
When the parameter K is of the order of unity, the device is called an undulator. The angular excursion of the electron beam is less than or comparable to the natural opening angle γ^{-1} in which synchrotron radiation is emitted, so that the radiation emerging from the device is concentrated in the smallest possible opening angle. Thus, an undulator produces radiation with very high spatial brightness (photons $\mathrm{sec^{-1}\ mrad^{-2}\ mm^{-2}}$). For an undulator with a large number of periods, interference effects in the radiation produced at the large number of essentially colinear source points result in a spectrum with quasimonochromatic peaks at wavelengths given by

$$\lambda = (\lambda_u/2n\gamma^2)(1 + K^2/2 + \gamma^2\theta^2)$$

Here θ is the angle of observation relative to the average electron direction and n is the harmonic number. When the undulator parameter K is much less than 1, only the fundamental peak ($n = 1$) is important. When K is approximately 1, the power in the fundamental is a maximum and the first few harmonics have appreciable intensity. The suppression of radiation at most wavelengths and the concentration of the radiation into one or a few quasimonochromatic peaks given by the above equation results in radiation of very high spectral brightness.

When K is much greater than 1, the fundamental has a very long wavelength and there are many closely spaced, intense harmonics. In this limit the device is called a wiggler, and the envelope of the spectrum approaches the familiar continuous spectrum of synchrotron radiation characteristic of bending magnets.

Reaching shorter wavelengths. High-



Brightness comparsion of radiation from a 30-pole, 2.3-tesla wiggler (upper dashed curve), a 1.2-tesla bending magnet (lower dashed curve) and a 30-pole undulator with a parameter K of 1.4 (solid curve). These sources are planned for the proposed Advanced Light Source at Lawrence Berkeley Laboratory. (Calculation by Kwang-je Kim, LBL.) Figure 5 field wigglers offer extended spectral range as compared with storage-ring bending magnets: A simple three-pole wiggler, which causes only one oscillation of the electron beam, extends the spectral range. Additional poles produce additional oscillations and provide higher intensity. Electromagnetic wigglers with fields up to 1.9 T are operating as sources of synchrotron radiation in Frascati, Italy, and at Stanford. There are superconducting wigglers with fields of 3.5 T to 6 T in Novosibirsk (USSR), Daresbury (England), and at the Photon Factory in Japan; in the US, superconducting wigglers are being prepared for use at Brookhaven.

From the equation for λ on page 54, we see that undulators can reach short wavelengths by using a short period or high electron energy. Because the field in an undulator decreases exponentially with the ratio of the gap to the period, the smallest gap is desirable. This had led to designs and proposals for variable-aperture vacuum chambers or variable-gap undulators situated inside the vacuum chamber. Such an arrangement would allow one to increase the aperture for the injection of the electrons, and then to reduce the magnet gap to the smallest value that is adequate for the damped stored beam. The minimum permissible aperture for the stored beam depends on the beam's energy, the average pressure and the parameters of the storage ring. New rings are designed to reduce the required aperture.

An experiment using a parasitic undulator on the PEP storage ring at SLAC will soon explore the approach of using high electron energy to reach short wavelengths with undulators. The 15-GeV electrons, usually used in colliding-beam studies, should readily generate fundamental undulator peaks as high as 30 keV, with far higher brightness than is available on other rings now in operation. There are similar plans for the 8-GeV and 30-GeV rings under construction at KEK in Japan.

Storage ring synchrotron radiation sources

Location	Ring (lab)	Electron energy (GeV)	Notes
China			
Beijing	BEPC (IHEP)	2.2–2.8	Parasitic*
Hefei	HESYRL (USTC)	0.8	Dedicated*
England			
Daresbury	SRS	2.0	Dedicated
France			
Orsay	ACO (LURE)	0.54	Dedicated
	DCI (LURE)	1.8	Partly dedicated
	SuperACO (LURE)	0.8	Dedicated*
Germany			
Hamburg	DORIS (DESY)	5.5	Partly dedicated
West Berlin	BESSY	0.8	Dedicated
Italy			
Frascati	ADONE	1.5	Partly dedicated
Japan			
Tsukuba	Photon Factory (KEK)	2.5	Dedicated
	Accumulator (KEK)	6–8	Partly dedicated*
	TRISTAN (KEK)	30	Parasitic*
Tokyo	SOR (ISSP)	0.4	Dedicated
Okasaki	UVSOR (IMS)	0.6	Dedicated*
Tsukuba	TERAS (ETL)	0.6	Dedicated
Sweden			
Lund	Max	0.55	Dedicated*
US			
Gaithersberg, MD	SURF (NBS)	0.28	Dedicated
Ithaca, NY	CESR (CHESS)	5.5–8	Parasitic
Stanford, CA	SPEAR (SSRL)	4.0	Partly dedicated
Stoughton, WI	Tantalus (SRC)	0.24	Dedicated
	Aladdin (SRC)	1.0	Dedicated
Upton, NY	NSLS I (BNL)	0.75	Dedicated
	NSLS II (BNL)	2.5	Dedicated
USSR			
Karkhov	N-100 (KPI)	0.10	Dedicated
Moscow	Kurchatov	0.45	Dedicated*
Novosibirsk	VEPP-2M (INP)	0.7	Partly dedicated
	VEPP-3 (INP)	2.2	Partly dedicated
	VEPP-4 (INP)	5–7	Parasitic

*In construction as of April 1983.

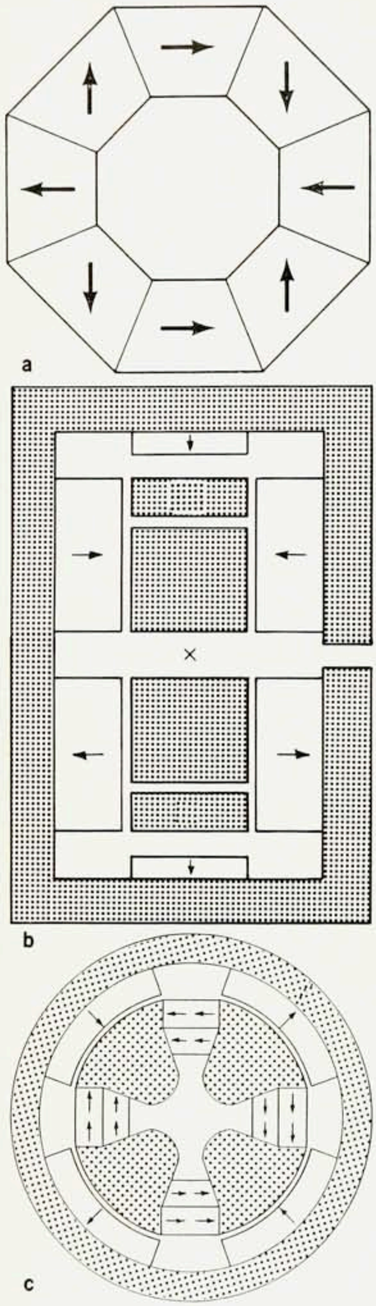
Permanent-magnet technology

Increasingly, physicists are making wigglers and undulators from permanent magnets,[19,20] using the rare-earth–cobalt alloy $SmCo_5$. The properties of this material make it possible to construct short-period magnets with higher fields than one can obtain with normal electromagnets and, in some cases, also higher than one can obtain with superconducting magnets. Experimenters at synchrotron radiation facilities in Brookhaven, Orsay, Novosibirsk, Tsukuba and Stanford have used permanent-magnet undulators with up to 60 periods (and parameters K just under 2) as sources of vacuum ultraviolet and soft x-ray radiation, that is, radiation of energy under 1 or 2 keV. With permanent magnets, one adjusts the energy of the quasi-monochromatic peaks by varying the gap or the electron energy. Most permanent-magnet devices now in use have been built using the pure rare-earth–cobalt design developed by Klaus Halbach of Lawrence Berkeley Laboratory. Halbach recently developed[19] a new hybrid design, using permanent-magnet material and steel, that gives a higher magnetic field than is attainable using only the rare-earth–cobalt alloy, the ratio of magnet gap to period being held constant for the comparison.

A 2-meter-long, 27-period hybrid wiggler[10] with a parameter K of about 10 is now under construction (see the cover of this issue) at Lawrence Berkeley Laboratory as a joint project with Exxon and the Stanford Synchrotron Radiation Laboratory. With a 1.2-cm gap, the magnet reaches a peak field of 1.2 T. The result is a spectrum with a critical energy of 7 or 10 keV when used in the SPEAR storage ring operating at 3 or 3.5 GeV, respectively. To provide the 1.8-cm aperture required for injection, the wiggler assembly incorporates a thin-walled variable-gap vacuum chamber.

An important feature of permanent-magnet systems is that the field stays the same when all linear dimensions are scaled by the same factor. In conventional and superconducting electromagnets the current density in the coils must increase to maintain the same field as the linear dimensions decrease. This places limits on the performance of short-period electromagnetic wigglers and undulators.

Permanent-magnet technology offers other possibilities relevant to synchrotron radiation research that



New permanent-magnet devices. Diagrams show design concepts in cross section. In the helical undulator (**a**) successive magnet segments are rotated to produce a field of constant amplitude that rotates in a helical fashion. The device produces circularly polarized radiation. The dipole (**b**) is suitable for use as a bending magnet in a storage ring. The stored beam, indicated by the cross, moves perpendicular to the figure. Dots indicate steel, and arrows show the direction of magnetization in permanent-magnet material. One varies the magnetic field in the gap by moving the small rectangular steel blocks. In the quadrupole (**c**) one varies the field by rotating the outer ring with its attached blocks of permanent-magnet material. Figure 7

have not yet been exploited. One example, suggested by Halbach, is a permanent-magnet helical undulator that would produce circularly polarized radiation. (See figure 7a.) The performance of such a device would equal or exceed that of a superconducting helical undulator such as the one used in the free-electron laser by John Madey and his collaborators at Stanford.

It is also possible that all storage-ring magnets, not only the wiggler and undulator insertions, can be made as permanent magnets. Figures 7b and 7c show conceptual designs developed by Halbach for storage-ring dipole and quadrupole magnets. In the near future, workers at LBL and Orsay will build prototypes of these magnets; their aim is to construct a small (almost 500 MeV) permanent-magnet storage ring for microlithography and free-electron lasers. In addition to reduced running costs, a ring with all permanent magnets offers attractive simplifications in operations, particularly in a fixed-configuration machine such as industry might use.

Power-density limitations. It is already clear that the factor that will limit the use of high-field, multipole wigglers in high-current, multi-GeV storage rings is our ability to cool surfaces struck by the high power density of radiation that these devices readily produce. The multipole wigglers currently in use at Stanford and Novosibirsk use stored 100-mA electron beams to generate radiation with a total power of about 3 kW and a power density of about 200 W/mrad. Devices now under construction will provide power densities that are higher by a factor of four or more. For example, the 54-pole 1.2-T permanent-magnet wiggler being built for the Stanford Synchrotron Radiation Laboratory will produce 750 W/mrad from 100 mA of 3-GeV electrons. The 6-pole superconducting wiggler and the 24-pole 1.5-T permanent-magnet wiggler being built for the National Synchrotron Light Source will each produce about 1 kW/mrad with 500 mA in the 2.5-GeV ring. The design of masks, mirrors, beryllium windows, crystals, gratings and other beam-line elements that can function under this thermal load is becoming very complex.

The quasimonochromatic nature of the spectrum from undulators means that they produce more useful photons—that is, more photons within a narrow bandwidth—for a given total radiated power than do wigglers or bending magnets. Thus we expect undulators to be ultimately the preferred sources.

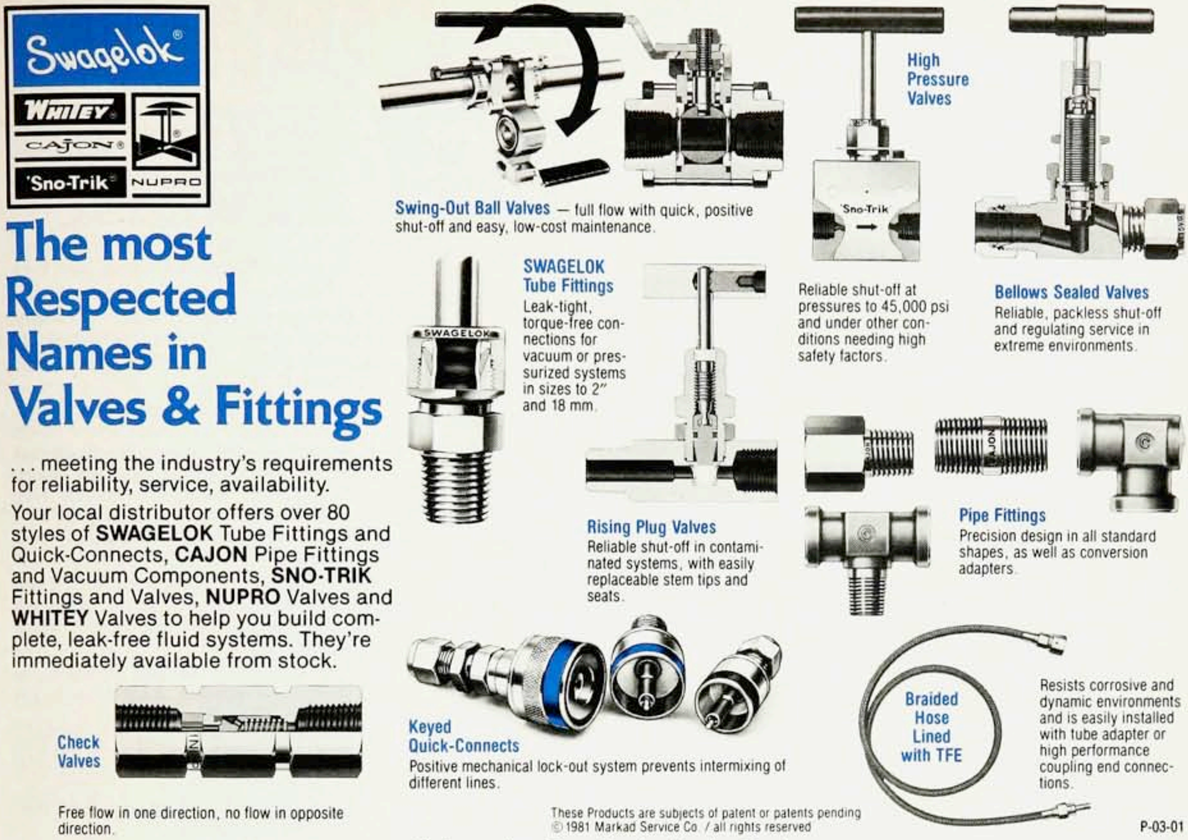
Research facilities

Facilities for synchrotron radiation research have expanded greatly in the past few years. Many of the facilities that are already in operation are making major increases in their research capabilities. They are doing this in two ways: by increasing the number of experimental stations, support staff and the amount of equipment, and by changing from being largely parasitic on research programs in high-energy physics to being partly or fully dedicated to synchrotron radiation research. Dedicated operation results in vast improvements in running conditions, including higher photon energy and flux, longer beam lifetime, higher brightness and improved stability. In addition, many new rings are now coming on-line as fully dedicated light sources, and several others are in construction. These new facilities will have immense research capability. The large number of simultaneously operating stations at a single facility means that operating costs per station-hour are quite low. Full-cost charges, as are made for proprietary research, range from \$40 to \$200 per station-hour.

The table on page 55 lists storage-ring sources of synchrotron radiation that are in operation or under construction around the world. In addition there are about six operating electron synchrotrons that are also used for synchrotron radiation research. As the table indicates, 20 storage rings now supply synchrotron radiation for research in 9 countries. Eight additional rings are under construction, four as dedicated light sources and four that will be used for other research as well. In addition, scientists are promoting laboratories dedicated to synchrotron radiation research in Australia, Brazil, Europe, India, Taiwan, the US and the USSR. The status of these proposals varies widely; some are in the early stages of discussion, while others have nearly complete designs and expect to begin construction soon.

Future facilities. As we mentioned earlier, the success of wiggler and undulator magnets as sources of synchrotron radiation has transformed our ideas about the design of research facilities. There are now proposals to construct rings that will accommodate a large number of these insertion magnets and make little or no use of the radiation produced in the bending magnets.

The first such proposal was made by the European Synchrotron Radiation Facility[15] group. For several years, working groups of scientists from many western European countries have considered various designs for an x-ray source optimized to give photons with energies up to 10–20 keV. Such a source would be based on a beam of high-energy (3.5–5 GeV), low-emittance electrons moving in a ring of up to 900-m circumference and capable of accom-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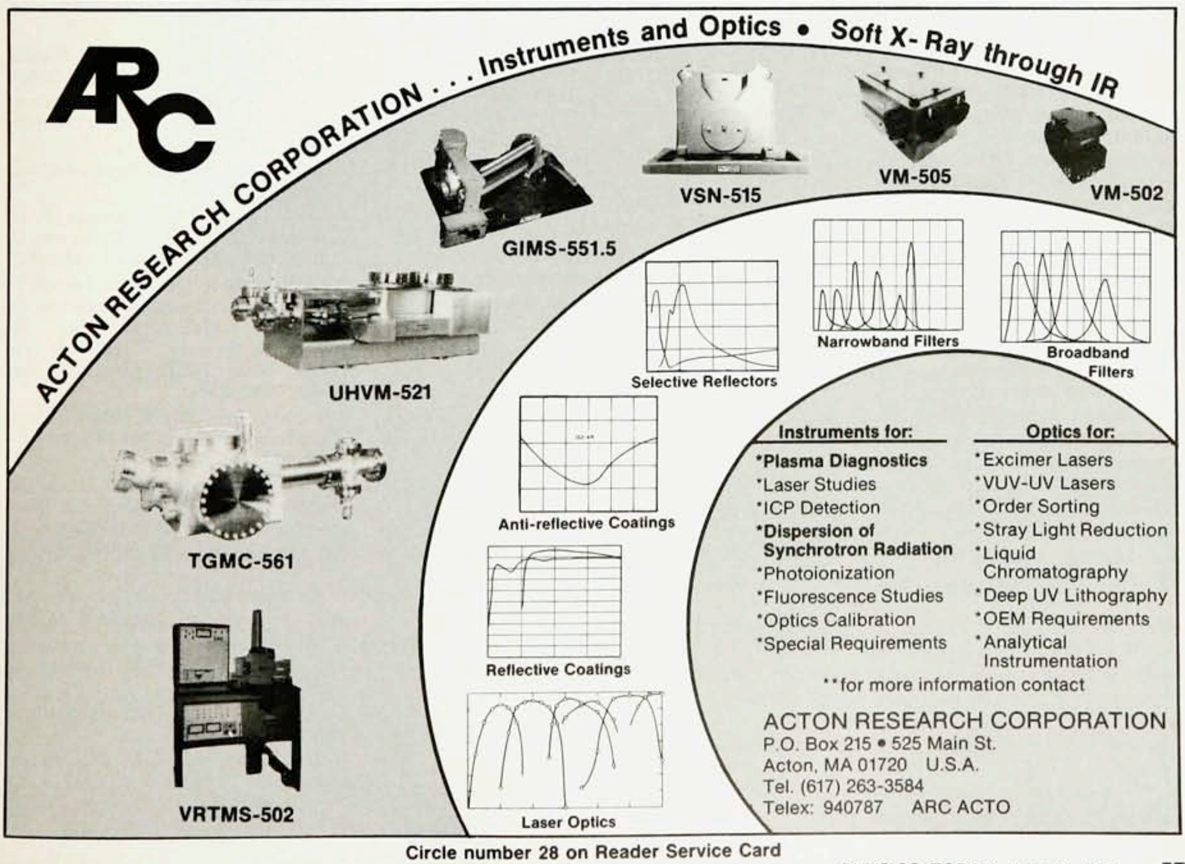
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modating about 40 wiggler and undulator insertions. The group will seek funds for the project from several western European governments.

A few months ago an important step was taken toward the realization of this proposal with the establishment of the European Synchrotron Radiation Project, with Bronislaw Buras of the Danish national physics laboratory Risø as director. The main task of the project is to prepare a site-independent proposal for the European Synchrotron Radiation Facility, discussing the scientific case, machine design and instrumentation. The project's initial offices are at CERN, and Sergio Tazzari of Frascati is the leader of the ring design group.

In 1982, Lawrence Berkeley Laboratory proposed construction of a 1.3 GeV wiggler and undulator storage ring, called the Advanced Light Source,[16] as the major experimental tool for a proposed new National Center for Advanced Materials to be built at LBL. (See the story on page 17.) This low-emittance source is designed to give high brightness in the vacuum ultraviolet and soft x-ray part of the spectrum, that is, the region below 1–2 keV. Its ring would accommodate 12 wiggler and undulator insertions around a circumference of 182 m, about the same circumference as the 2.5-GeV ring of the National Synchrotron Light Source. Funds for the National Center for Advanced Materials and the Advanced Light Source are in the President's budget for FY 1984.

More recently, our own group at Stanford has begun development of a proposal for a pair of wiggler and undulator storage rings that would use the same tunnel, about 530 meters in circumference.[17] One of the rings would contain low-energy electrons of 1–2 GeV and would give synchrotron radiation with high brightness in the vacuum ultraviolet and soft x-ray part of the spectrum. The other, a high-energy ring operating at 5–6 GeV would reach x-ray energies. Beam lines would enter the same experimental hall in an alternating fashion. The rings would have low emittance and would each be capable of accommodating about 30 wigglers and undulators.

The similarities among the above proposals—large circumference, low emittance—are the result of the common aim to produce high-brightness radiation from many wigglers and undulators. Achieving the high performance sought in these rings presents several technical challenges. For example, positive ions collecting around the negatively charged beam can spoil the beam's emittance. These positive ions, which are produced in the residual gas by the circulating electron beam, can be removed by applying electric fields, or they may be allowed to drift away by leaving large spaces between bunches or groups of bunches of electrons. However, these solutions have limitations and drawbacks. A perfect solution is to use positrons rather than electrons for the stored beam.

The construction of a high-quality vacuum system is another technical challenge. The quality of the vacuum is extremely important to the proposed rings because the performance of wigglers and undulators, particularly the highest photon energy and brightness attainable in the fundamental interference peak, depends on the smallest magnet gap that one can use without compromising the lifetime of the electron beam. The lifetime of the stored beam due to Coulomb scattering on the residual gas varies directly as the square of the aperture and inversely as the average pressure.[17] Therefore, these new rings try for average operating pressures of 10^{-9} Torr or less.

Another goal of the new rings is electron bunch lengths shorter than 100 picoseconds. Such pulses of electrons would emit sharper pulses of radiation than are now available, thus extending capabilities for dynamic experiments and improving the resolution of time-of-flight systems. Filling the ring with only one or a few equally spaced short bunches provides a long interpulse period. Achieving reasonable stored current in this timing mode will require much work on instabilities, losses associated with higher modes, and other technical problems.

Synchrotron radiation has already had an immense scientific impact, and it has an even greater future potential. Realizing this potential presents many challenges in the development of more powerful sources and associated instrumentation such as mirrors, monochromators and detectors. An expanding community of scientists and engineers all over the world is making excellent progress in meeting these scientific and technological challenges. It is likely that even more important, yet to be identified, problems will become soluble as capabilities grow.

In future PHYSICS TODAY articles on synchrotron radiation, workers in many fields will give accounts of the accomplishments and opportunities made possible by this most remarkable research tool.

* * *

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