MANY NATIONS BUILD THE LATEST IN SYNCHROTRON LIGHT SOURCES

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Synchrotron light sources under construction. The Advanced Light Source in Berkeley (top) should operate by 1993. The European Synchrotron Radiation Facility in Grenoble (bottom) is scheduled to operate by 1994. The Advanced Photon Source at Argonne (center) is at an earlier stage.

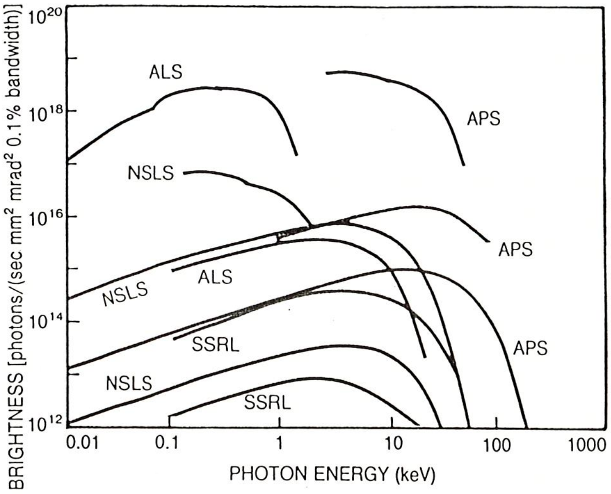
At a number of construction sites around the world, crews are laboring in and around large circular tracks to install the accelerators and storage rings that will form the basis of new synchrotron radiation facilities. Most of the budding facilities are designed to produce synchrotron radiation, in the soft- or hard-x-ray regions, that is far brighter than available sources can provide. They are sometimes described as the "third generation." According to this rough categorization, the first generation consists of circular accelerators originally intended for other purposes: They provide synchrotron radiation to parasitic experiments or, in some cases, they have become partially dedicated to such uses. The second generation comprises facilities specifically designed to support synchrotron radiation experiments, with the radiation produced primarily as electrons or positrons curved in the field of the machines' bending magnets. The third-generation machines, by contrast, are designed to optimize the radiation that is produced as the electrons or positrons traverse devices known as wigglers and undulators. The new machines will complement existing facilities, and they will provide more opportunities for the growing user community.

Undulators and wigglers

In all synchrotron radiation facilities, some combination of accelerators boosts electrons or positrons to the desired energy and sends them into a storage ring. As the electrons arc around the bending magnets in the ring, they emit synchrotron radiation. The radiation at any one instant is characterized by its spatially narrow cone of emission, which has a continuous and wide spectrum. The opening angle for this cone is $1/\gamma = mc^2/E$, where m is the electron rest mass and E is the total electron energy. The radiation from a bending magnet maintains this narrow angular divergence in the vertical direction but spreads horizontally over several degrees as the electron curves around in the magnetic field.

By contrast, wigglers and undulators are devices inserted into straight sections between the bending magnets. They consist of linear arrays of magnetic dipoles with alternating polarities that produce fields perpendicular to the plane of the beam. These devices may be a few meters long and may incorporate up to a hundred or so poles (fewer for wigglers). As a charged particle traverses the magnetic regions, in which the field vectors point first upward and then downward, it curves first one way, then the other, in the orbit plane. Snaking along in this manner, the electron or positron constantly emits photons.

Undulators and wigglers have the same construction but produce different types of radiation. The difference is determined by a certain parameter, K, which is a measure of the bending angle of the electron per pole in units of $1/\gamma$. The value of K depends on the magnetic field strength and the period of alternation of the magnet poles. When K is larger than 1, the electron path swings outside the radiation cone, the radiation adds incoherently and the device is said to be a wiggler. As shown in the figure on page 18, the radiation from a wiggler has roughly the same spectral shape as that from a bending magnet, but it is brighter by a factor roughly equal to the number of magnet poles. (Brightness is a measure of the number of photons per second per solid angle per source area, and is usually specified in terms of some percentage of the bandwidth



Radiation from bending magnets (green), wigglers (blue) and undulators (red) differs in brightness and spectral range. Sample curves are calculated from the parameters of the Stanford Synchrotron Radiation Laboratory (SSRL), the National Synchrotron Light Source (NSLS), the Advanced Photon Source (APS) and the Advanced Light Source (ALS).

of the bandwidth $d\lambda/\lambda$. The wavelength at which the spectrum peaks can be tuned by changing the strength of the magnetic field.

When K is on the order of or less than 1, the electron does not move outside the radiation cone, so that the radiation cones from successive bends overlap and interfere coherently with one another. In this case the device is an undulator. The undulator radiation spectrum is characterized by sharp peaks at some fundamental spectral wavelength, with successively less intense peaks at higher harmonics. The undulator thus produces a laser-like beam of intense radiation at specific wavelengths, and these wavelengths are tunable by changes in the size of the vertical gaps in the magnets. The undulators on the new machines should produce brightnesses of 10^{18} or 10^{19} photons/(sec mm² mrad² 0.1% bandwidth).

The third-generation machines facilitate the use of these so-called insertion devices by featuring numerous long straight sections and producing electron or positron beams with low emittances (emittance is the product of the beam's width and its divergence). While a large number of existing radiation facilities already have emittances that are considered quite low (on the order of 100 nm rad), many of the new machines will have emittances that are more than a factor of ten lower.

Both wigglers and undulators represent ways to increase the brightness of the radiation, facilitating some experiments that otherwise might not be possible. But other experiments are more limited by flux than by brightness. For such experiments, some second-generation machines, while not being optimized for undulators, have insertion devices with fluxes nearly comparable to those expected for the new rings.

Hard x-ray sources

Three new facilities aimed at the hard x-ray region are the 6-GeV European Synchrotron Radiation Facility in Grenoble, France; the 7-GeV Advanced Photon Source at Argonne National Laboratory; and the 8-GeV SPring-8 facility being built in Japan. Of these three, the ESRF, funded by a collaboration involving 11 European nations, is the farthest along in construction. The ring, 884 m in circumference, has been situated next to the Institut Laue–Langevin. (See PHYSICS TODAY, May 1985, page 19, and December 1986, page 65.) A linac will provide the initial acceleration to 200 MeV, and a booster synchrotron will take the electron to its final energy for injection into a storage ring. The linac, a turn-key instrument, is being assembled, and construction of the synchrotron booster and the storage ring has begun. (See the photo on page 17.) ESRF will eventually have 30 beam lines originating from insertion devices (either wigglers or undulators), although only 7 will be operating by 1994, when the facility is scheduled to begin experiments. The wigglers are expected to produce radiation with wavelengths of 0.5 Å, but very-high-field three-pole wavelength shifters can be used to get down to wavelengths of 0.05 Å. The fundamental radiation from the undulators should peak at 14.4 keV, corresponding to a photon wavelength of 0.86 Å.

Ground was broken last June at Argonne for the Advanced Photon Source, which is scheduled to begin operation in 1995. Only a modest amount of site preparation has been done so far, but the pace should step up with the arrival of spring. In the APS, a 200-MeV linear accelerator will produce electron pulses, which will then be converted to a low-energy positron beam by collision with a tungsten target. A linac will accelerate the positrons to 450 MeV, and a booster synchrotron will take them to 7 GeV before injection into the 1104-m-circumference storage ring. The APS ring is slated to store positrons with a beam current of 100 mA. (Positrons are used to produce a more stable beam: Unlike electrons, they repel rather than attract the ions generated from the residual gas molecules and hence do not degrade the vacuum locally.)

The 40 straight sections allow for the placement of 34 insertion devices. Beam lines will be built for each of these insertion devices by groups of users. David Moncton, director of the APS, told us that by mid-March, 19 applicants had submitted proposals to build beam lines. (See the box on page 19)

Although costs are difficult to compare, the APS price tag of $456 million is roughly equivalent to that of the ESRF. The APS operates at only a slightly higher energy than the ESRF (7 vs 6 GeV), but that extra energy allows a *single* undulator at the APS to provide radiation over the entire range from 4 to 40 keV. The ESRF can cover roughly the same energy range, but with a gap in the tuning range for a given undulator. Ruprecht Haensel, director of the ESRF, explained to us that this difference between the two facilities reflects different philosophies concerning the use of the beam lines: Whereas the APS is being designed to give total flexibility to the teams who build and use each beam line, the ESRF will optimize each beam line for a specific type of experiment.

Japan's SPring-8 is being built in Harima Science Garden City, 100 miles west of Osaka, by the Institute of Physical and Chemical Research (RIKEN) and the Japan Atomic Energy Research Institute. Scheduled for completion in 1998, the facility will feature a 250-MeV linac, a 1-GeV positron linac and an 8-GeV booster synchrotron. The ring will have a circumference of 1 436 m. For placement of insertion devices, the ring will have 36 straight sections that are 6.5 m long, and another 4 that are 36-m long. Already 24 groups of users have submitted proposals to build beam lines at SPring-8.

Soft x-ray sources

A number of third-generation machines will produce soft x rays. One of these, the Advanced Light Source at the Lawrence Berkeley Laboratory, is well along toward its projected start-up date two years from now. Beneath the dome that once sheltered the 184-inch cyclotron (see PHYSICS TODAY,

Will Users Have to Pay Fees?

The US has built and operated many large facilities such as the synchrotron radiation facilities for the benefit of public users. These users are not charged for their time on the machines, provided they publish the results of their experiments in the scientific or technical literature. But Congress is now looking at the large expenditures on such user facilities and wondering if more of the costs should be shouldered by users. Thus a provision in the Budget Reconciliation Act instructs the Department of Energy to explore ways "to reasonably increase revenues to the United States through users fees" and report back this spring. The study is to include facilities of all agencies, not just DOE.

Among other things, the DOE will have to study how much the government might net from user fees. Louis Ianniello, acting associate director for basic energy sciences at DOE, points out that a majority of the users from universities or nonprofit groups are supported by various government contracts, so that user fees imposed on this group would simply transfer funds from one government agency to another.

The Federal facilities also now attract many users from industry. The percentage of industrial researchers is especially high at synchrotron radiation facilities, which were built in part to spur participation by US industries in advanced materials research. Arthur Bienenstock, director of the Stanford Synchrotron Radiation Laboratory, fears that user fees "would be challenged by industry and would nearly eliminate corporate research at SSRL at a time when it should be encouraged." That would be regrettable, he feels, especially at this time, when "basic and long-term corporate research has decreased markedly over the past decade." Martin Blume, deputy director of Brookhaven National Laboratory, which operates the National Synchrotron Light Source, another facility used heavily by industrial researchers, argues that industrial firms often take a very short-term view of their investments and might hesitate to pay fees for the longer-term research that they currently pursue at the national facilities. In a letter expressing concern over the user fees, Frank Sprow, vice president of Exxon Research and Engineering, stated that "rather than increasing revenue for the government, the result would inevitably be a significant decrease in research for the country."

Under present arrangements many users contribute to the capital expenses of building some Federal facilities. When NSLS was being built, Brookhaven instituted a program of so-called participating research teams. These groups of researchers, be they from industry, academia or government, apply for permission to set up experimental equipment at the facility for a period of three years. They are committed to make 25% of the time on their equipment available to the public users. Blume points out that users at NSLS have provided about $120 million in instrumentation, with $40 million of that coming from industry. For comparison, the total construction cost was about $50 million. The Advanced Photon Source at Argonne and the Advanced Light Source at Lawrence Berkeley Laboratory are counting on users to provide most of their beam lines and experimental equipment. David Moncton, director of the APS, estimates that the 19 proposals received so far to construct beam lines there represent a potential investment of about $200 million. Blume concludes that the Federal government is mistaken if it believes that "there is a pot of gold at the end of the light source rainbow."

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May 1989, page 19), construction of the injection linac is complete. It has been tested with its design energy of 50 MeV, although not yet at full current. The injector will feed a booster synchrotron that will raise the electron energies to 1.5 GeV before injecting the electrons into the storage ring. Installation of the booster is all but complete. The facility will yield radiation in the xuv region, that is, from 10 eV to 1 keV, although the undulator from this facility should yield radiation in the fifth harmonic that will extend to 2.5 keV.

The storage ring at the ALS has 12 straight sections, of which 10 are available for insertion devices, and 24 bending magnets available for development. The $100 million construction budget will pay for four insertion devices (three undulators and one wiggler) and for two undulator beam lines. The remainder of the insertion devices and beam lines are the responsibility of groups of users, under arrangements similar to those by which user groups at the APS will build the beam lines at that facility.

In France, the 800-MeV SuperACO accelerator has been operating for more than three years at the Laboratoire pour l'Utilisation du Rayonnement Electromagnétique in Orsay. This ring is run with positrons and features six straight sections to accommodate insertion devices. Four of them are currently operated. The emittance of the ring is lower than the emittances of most existing machines, although not as low as those expected from many of the rings now under construction.

Several third-generation xuv synchroton radiation facilities are under construction in the Europe. One, a light source at Trieste, Italy, with capabilities similar to the ALS, is being built by a government-funded private corporation whose director is Carlo Rubbia, director general of CERN. Known as ELETTRA, this machine will have a 259-m-circumference storage ring with maximum energy of 2 GeV and 11 straight sections dedicated to hosting insertion devices. A linac will inject electrons into the storage ring at full energy. Another third-generation vux light source is being built at MAX-Lab in Lund, Sweden, which currently operates a 550-MeV ring called MAX. The new machine, MAX II, would be a 1.5-GeV, low-emittance ring.

Several other European xuv synchrotron projects are awaiting approval. One is proposed by Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, a largely government-funded corporation in Berlin. As a successor to its current 800-MeV synchrotron ring, known as BESSY I, the corporation would like to build BESSY II, a 1.7-GeV ring with 10 or 12 straight sections. Another proposal is for the Daresbury Advanced Photon Source to be built at the Daresbury Laboratory in Cheshire, England. Operating in the vuv and soft-x-ray regions, it would complement the existing 2-GeV synchrotron radiation source run at Daresbury since 1980 by the UK's Science and Engineering Research Council. The feasibility study for the new source envisions a variable-energy (0.5–1.2 GeV) racetrack design with two long straight sections equipped with undulators and wigglers. Orsay is also considering the construction toward the end of the decade, of a 2.15-GeV ring that would replace both Super-ACO and DCI, another x-ray facility in operation since 1975.

Two more xuv facilities are planned in the Far East. A 1.3-GeV ring is being built at the Synchrotron Radiation Research Center in Hsinchu, Taiwan. And the construction of a 2-GeV synchrotron facility, the Pohang Light Source, has begun at the Pohang Institute of Science and Technology in South Korea. Posco, a steel company, has funded at least half of the approximately $200 million project, with the rest being provided by the government. The ring has a 280-m circumference, 12 straight sections and a 2-GeV linac as a full-energy injector.

Other works in progress

A number of nations are building other synchrotron radiation facilities. Some are designed primarily for research on x-ray lithography. Others, while not having either enough straight sections or high enough brightnesses to qualify as third generation, will nevertheless be vaulable resources for the large numbers of researchers who would like access to these machines. After all, notes Herman Winick (Stanford Synchrotron Radiation Laboratory), the intensitites of bending magnets are still 100 000 times those of x-ray machines.

The Laboratorio National de Luz Sincrotron in Brazil is constructing a 1-GeV synchrotron radiation facility in Campenas, which is scheduled for completion by 1992. That ring would be followed by a 2- to 3-GeV ring by 1995. The Kurchatov Institute in the USSR has contracted with the Institute for Nuclear Science and Research in Novosibirsk to build a 2.5-GeV ring, called Siberia II, to be located at the Kurchatov Institute. The injector will be an existing 450-MeV accelerator, Siberia I, which, in the words of Ednor Rowe (Synchrotron Radiation Center at the University of Wisconsin), "is a synchrotron facility in its own light." In the People's Republic of China, an 800-MeV storage ring patterned after BESSY I has begun to operate at its design specifications in the last year. It is run by the Hefei National Synchrotron Radiation Laboratory (HESYRL) in the province of Anhui. India's Center for Advanced Technology in Indore is building a 450-MeV machine known as Indus, and has plans for one at higher energy.

The most unusual project is one undertaken at the Aarhus storage ring (known as ASTRID) in Denmark, which was built for heavy ions. The accelerator has been operating with ions since 1990, and now scientists at the Institute for Synchrotron Radiation at Aarhus University are adding an electron injector so that the ring can operate with either ions or electrons.

In general, synchrotron sources facilitate a wide variety of measurements—absorption, diffraction, spectroscopy and so forth—on materials as diverse as DNA, silicon, catalysts and polymers. The high brightness opens the door for many measurements that were previously very time consuming—or not possible at all. The rapid pulsing combined with the high brightness will also enable dynamical studies of such things as ultrafast chemical reactions: The new machines essentially replace a photographic capability with a cinematic one. The applications of soft- and hard-x-ray machines are complementary, and many investigations require machines of both types.

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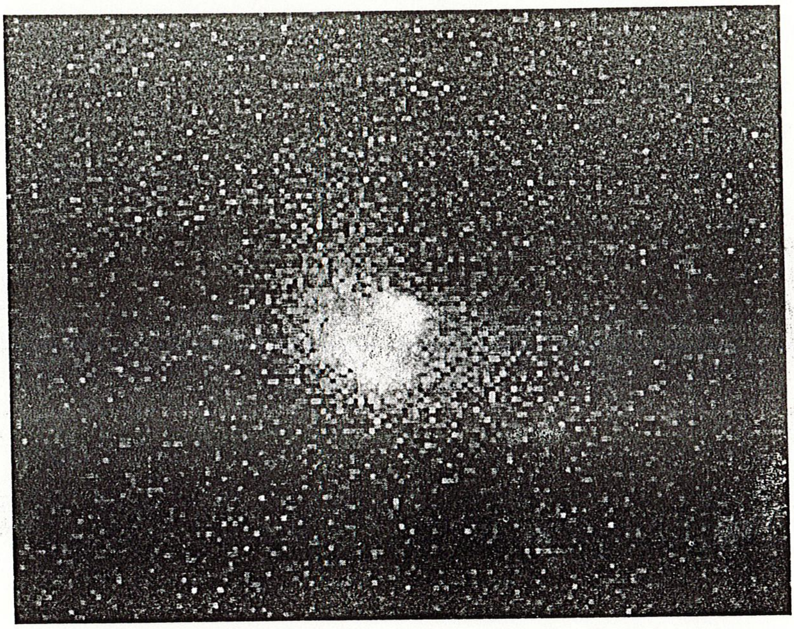
A Surprise from the Predictable Comet Halley



A sudden eruption on Comet Halley enveloped it in a cloud of dust that is 300 times brighter and about 20 000 times larger than its nucleus. (The width of the photograph above corresponds to 71 arcseconds, or about 700 000 kilometers at the distance of Halley.) Previously the comet had behaved as expected, reappearing in our solar system right on schedule. At that time, our visitor had also generated a cloud of dust, but such a phenomenon was expected when the comet was close to the Sun: The solar energy sublimated the water ice on this "dirty snowball," and the outward-moving water vapor carried the dirt particles off the surface. But as the comet gradually receded from the Sun, its surface temperature fell back and the dust cloud virtually disappeared. Then, on 12 February, as Comet Halley was between Saturn and Uranus, some two billion km from the Sun, comet trackers Olivier Hainaut and Alain Smette of the European Southern Observatory in Chile found the comet to be greatly enlarged, as shown in the above photo. Three days later, another Halley watcher, Karen Meech (University of Hawaii) independently saw the vast cloud of dust. Smette subsequently made spectral measurements and determined that the comet's light was consistent with sunlight reflecting from dirt particles. Richard West of ESO reports that through 17 March the comet was still extremely active, with the shape of the cloud changing from night to night. This behavior just deepens the mystery, West feels.

So what happened? The continuing activity seems to rule out the already distant possibility that the comet collided with another body. It is also improbable that the cloud resulted from effects of the comet's interaction with the solar wind. More plausible, speculates Zdenek Sekanina of the Jet Propulsion Laboratory, is some type of dynamic process that opened a crack in the comet's crust, permitting the frozen carbon monoxide or carbon dioxide to sublime and drive dirt off the surface. Astronomers are peering at Comet Halley now with new interest, but will they be able to get an answer to this mystery before Halley retreats from view for another 76 years?

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