Momentum Builds for New Synchrotron Source

A national steering committee will guide the proposed $160-million x-ray center through the mazes of technical and political approval

With all the attention being given to reducing the U.S. deficit, it would not seem the best moment to ask for a new $160-million research facility. But, buoyed by a National Academy of Sciences report last summer giving the project the highest priority and spurred by imminent European competition, American synchrotron radiation researchers are accelerating their efforts to try.

Aiming for a place in the fiscal 1988 budget 2 years from now, researchers are establishing a 33-member steering committee comprising accelerator specialists and synchrotron light users from across the country to coordinate the drive. Among the committee's chief objectives are securing agreement on the basic design and parameters of the electron storage ring that generates the radiation and helping to resolve as early as possible the always sticky problem of site selection.

Already in the running as hosts for the new facility are Argonne National Laboratory, Brookhaven National Laboratory, and the Stanford Synchrotron Radiation Laboratory. In addition, a laboratory built from the ground up on a new site is not out of the question. Meanwhile, to provide a mechanism for funding its work, the steering committee is formally associated with the Oak Ridge National Laboratory. Because Oak Ridge is not competing for the new synchrotron source, it also serves as a neutral base for operations.

The object of all this attention is a synchrotron light source that will generate beams of short-wavelength (hard) x-rays more than a thousand times brighter than now available.* The current rule of thumb is that the ratio of the brightness of the new machine to that of present synchrotron sources is as great as the brightness ratio of the latter sources to copper x-ray tubes, which has already been enough to cause a revolution in x-ray spectroscopic and structural studies of matter ranging from atomic vapors to biological macromolecules.

While it is straightforward to extrapolate for established techniques the advances a leap in brightness of this magnitude will make possible, researchers have a harder time forecasting what new capabilities will also arise. They point out that the advent of dramatically higher brightness has always stimulated progress in quite unexpected ways. One of the more spectacular possibilities is that the brightness of the source will make possible, in principle, three-dimensional images of the contents of living cells by x-ray holography.

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More generally, high brightness translates into (i) higher spectral resolution for a given measuring time, (ii) shorter measuring time for a given spectral resolution, (iii) higher spatial resolution for experiments that scan across surfaces, and (iv) measurable signals from more dilute species. And, since synchrotron light comes in pulses, which can be as short as 10 picoseconds, higher brightness makes time-resolved measurements of dynamic phenomena, such as phase transitions, easier.

Some glimpses of the future opened by the availability of high brightness synchrotron sources were reported in October at the annual user's meeting at Stanford. One was provided by Keng Liang of the Exxon Research and Engineering Company, Annandale, New Jersey. Liang, together with Paul Fuoss of Bell Laboratories, Holmdel, New Jersey, and Exxon colleagues Gerry Hughes and Peter Eisenberger used the newly developed technique of glancing angle surface x-ray scattering (*Science*, 23 September 1983, p. 1274) to look at the structure assumed by oxygen chemisorbed on copper surfaces.

Because of their low atomic number, oxygen and other typical adsorbed species, such as hydrocarbons, do not scatter x-rays strongly, making it hard to measure a signal that is already small, owing to the small number of atoms on a surface. However, low atomic number compounds are the ones of most interest in the study of such economically important processes as the heterogeneous catalysis of chemical reactions.

There are two interlocking ingredients in achieving high brightness. One is the electron beam and the other is the means by which synchrotron light is squeezed out of it. If approved and built, the new synchrotron source would be the first that optimized both.

On the accelerator side, the brightness could be enhanced by storing a higher beam current, since more electrons emit more photons. But brightness increases faster by confining the trajectories of the electrons for a given current. To minimize the source area, the beam cross section must be as small as possible. And to minimize the solid angle into which radiation is emitted, the electrons must have velocity components perpendicular to their ideal orbit that are as small as possible.

The quantity that measures these properties of the trajectories is called the emittance. The emittance of the new machine will be one-tenth or less that in some existing facilities built expressly to produce synchrotron radiation, such as the National Synchrotron Light Source at Brookhaven, while the stored current will be about the same or even a bit less. Brookhaven, in turn, has two storage rings with emittances about one-fourth that of Stanford's ring, although the latter is now being upgraded. Stanford's was originally a high energy physics machine—and still is half the time.

A low emittance also plays a crucial role in generating synchrotron radiation in the new light source. Synchrotron radiation comes when relativistic electrons follow curved trajectories, with the number of photons increasing rapidly as the energy of the electrons grows and the radius of curvature of their path shrinks. Circular electron machines emit a broad

*There is some specsmanship in citing numbers like brightness or spectral brilliance, as it is also called. In the end, the only number the experimenter cares about is the count rate in a detector. There is no source characteristic that maximizes the count rate for every experiment. The new synchrotron source is designed to optimize the brightness, which is defined as the number of photons per second per unit bandwidth ($\Delta\lambda/\lambda$ = 0.1 percent), per square millimeter cross-sectional area of the light source, and per square milliradian solid angle into which radiation is emitted. Brightness is the quantity that is conserved in optical systems and is therefore a more intrinsic measure of the source than such characteristics as intensity, which can be changed by focusing.

spectrum of synchrotron light when the electrons pass through the dipole or bending magnets that define their orbits. The newest electron storage rings dedicated to synchrotron radiation, though of improved emittance as compared to high energy physics machines, were designed primarily to generate ultraviolet and x-radiation from bending magnets.

As it happened, however, researchers at Stanford and elsewhere discovered in the late 1970's the ability of so-called insertion devices to dramatically enhance the photon flux (*Science*, 18 Mar. 1983, p. 1309). Insertion devices sit in straight sections of a storage ring that normally do not emit light. Arrays of magnets a few meters in length twist the electrons into sinusoidal trajectories (or, in some variations, helical paths), which causes the emission of radiation.

One type of insertion device, called a wiggler, has a stronger magnetic field than a bending magnet does, which violently shakes the electrons and thereby boosts the photon flux as compared to that from a bending magnet by roughly the number of periods in the sinusoidal trajectory. The experiment reported at Stanford by Liang used the new 54-pole permanent magnet wiggler built by an Exxon–Lawrence Berkeley Laboratory–Stanford collaboration. Powerful wigglers built from superconducting magnets are also in operation at the Daresbury Laboratory's Synchrotron Radiation Source in the United Kingdom and at the Photon Factory in Tsukuba, Japan.

A related kind of insertion device is the undulator, which has a relatively weak field that gently bends the electrons. The gentleness is the key to a unique feature of the undulator. At any instant, the synchrotron light from any curving electron is emitted into a cone with an "opening angle" that is inversely proportional to the electron energy. Because the undulator bends electrons through an angle that is less than this opening angle, there is an interference between light wave emitted from successive cycles of the sinusoidal trajectory. The interference compresses the light into a few relatively narrow bands, as compared to the broad continuous spectrum from bending magnets and wigglers. The wavelengths of the bands can be selected by adjusting the magnetic field strength or, less conveniently, the electron beam energy or the period of the undulator.

Because of the interference effect, undulators are more effective than wigglers in enhancing the brightness over bending magnets. The brightness of the emitted radiation increases as the square of the number of periods (N). But there is an important proviso. The increase comes only if the emittance of the electron beam is low enough. The N^2 increase in brightness means that light from a 100-period undulator could be 10,000 times brighter than that from a bending magnet on the proposed new synchrotron source. Undulators retrofitted to existing storage rings with higher emittances would have a smaller though still considerable effect on the brightness.

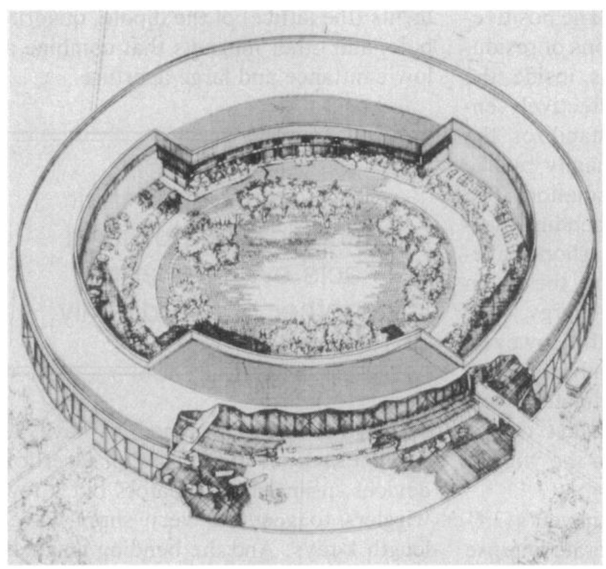
Undulators have another feature that is just as important as their brightness and which also traces to the interference effect. Researchers can use only a small part of the broad wiggler spectrum at any moment, so the unused radiation is thrown away and dissipated as heat in the experimenter's optical system. The x-ray beam from the Stanford 54-pole wiggler is powerful enough to melt its way through metal plates, and a comparable instrument in the new machine would put out ten or more times as much radiation. However, while the overall power from an undulator is smaller than that from a wiggler, because the light is concentrated in narrow bands, it is mostly used, and the heat dissipation problem, if not negligible, is easier to handle.

While wigglers are being inserted into the straight section of old storage rings as quickly as research programs and funding allow, undulators require more thought. For one thing, the range of wavelengths accessible by varying the magnetic field of a given device is limited, and it is impractical to keep changing the electron beam energy in a multi-user facility. One solution, being implemented at Stanford, is to build an array of undulators that collectively cover the desired spectral range.

Although plans to retrofit other existing storage rings with undulators are also under way, synchrotron researchers quickly realized that the forefront of their field would soon lie in a low-emittance electron storage ring designed specifically for and equipped primarily with undulators. The proposed synchrotron source is just such a facility. European scientists have plans for a comparable facility and may be able to get an earlier start than the Americans. However, the usual politicking over siting has yet to subside and full funding is not yet assured (*Science*, 27 July 1984, p. 391, and 14 Dec. 1984, p. 1294).

In the United States, politicking of a different sort led in the fall of 1983 to a Department of Energy (DOE)–sponsored study headed by Eisenberger and Michael Knotek of the Sandia National Laboratories. This panel established that the first priority for a new synchrotron radiation facility should go to a source optimized to generate high-brightness hard x-rays (which could also produce longer wavelength vacuum ultraviolet and soft x-radiation) rather than to one specializing in the longer wavelengths (which could produce no hard x-rays) (*Science*, 2 Dec. 1983, p. 995). Subsequently, a National Academy of Sciences committee ranked the proposed x-ray source over a new neutron source, which is an even more expensive facility that will soon be needed as U.S. research reactors wear out (*Science*, 17 Aug. 1984, p. 704).

Although it is unlikely that any federal agency other than DOE, which funds both Brookhaven and Stanford, would take responsibility for the proposed new source, the agency has made no commitment so far beyond funding the steering committee. However, DOE's Energy



Superbowl?

Stanford, which hosted this year's Superbowl, would also like to build this Superbowl-sized synchrotron radiation facility. Positrons enter the ring from an injection accelerator through the straight section at the top left. Experimental stations lie outside the ring (shown in the cutaway) under the circular shed. Offices and laboratories are in the arcs inside the storage ring at the top and bottom. [Source: Stanford Synchrotron Radiation Laboratory]

Research Advisory Board is examining the Academy's recommendations and will issue its response next month.

With the question of priorities settled, synchrotron researchers are organizing to see their project come to fruition. A convocation of those likely to be directly involved took place from 1 to 3 October at the Ames Laboratory on the Iowa State University campus.† One outcome was the national steering committee, which is being assembled by Eisenberger. If the 33 members nominated accept, the committee will meet late this month to elect a permanent chairman and to work on refining the critical machine parameters.

At the Ames meeting, accelerator specialists and synchrotron light users settled on a machine of beam energy 6 billion electron volts (GeV) and circumference 800 meters, which stores positrons rather than electrons. The positively charged positrons repel ions of residual gas or impurity species inside the vacuum chamber, which effectively enhances the vacuum and stabilizes the beam. The energy is set mainly by the wavelength of undulator radiation. The smooth spectra emitted by bending magnets and wigglers have a short-wavelength cutoff determined by the beam energy—the higher the energy, the shorter the cutoff wavelength. However, the shortest wavelength band emanating from an undulator comes at longer wavelengths than a bending magnet cutoff, which in turn is longer than the wiggler cutoff.

It works out that Brookhaven's 2.5-GeV storage ring can generate intense fluxes of x-rays down to at least 0.6 angstrom from bending magnets, but one needs a 6-GeV ring to get this wavelength from an undulator. The choice of 0.6 angstrom is far from arbitrary. The primary or K absorption edges of about half the elements are at this wavelength or longer, as are all the secondary L edges. Moreover, undulators also emit weaker but still serviceable fluxes of light at odd harmonics of the fundamental wavelength (third harmonic at wavelength $\lambda/3$, and so on). The 0.6-angstrom wavelength is also convenient for x-ray diffraction and high-resolution x-ray scattering experiments.

The ring circumference is set by the properties of the electron beam, the emittance in particular. All other things being equal, a storage ring with a large circumference has a smaller emittance than a more compact ring, partly because electrons behave better when they do not have to turn sharp corners. The first cut in both Europe and the United States at designs for a 6-GeV storage ring mainly involved scaling up the 2.5-GeV machine at Brookhaven.

Lately, accelerator specialists have appreciated the seriousness of a second characteristic, called the dynamic aperture. A large aperture permits accumulating, in a reasonable amount of time, an intense beam of electrons into the storage ring from an injection accelerator, which among other things means accepting electrons from the injector without disturbing those already stored. Simply scaling Brookhaven's 2.5-GeV design to 6 GeV results in a minuscule dynamic aperture. Recently, accelerator scientists at Stanford and Brookhaven have independently devised modified arrangements (the lattice) of the dipole, quadrupole, and other magnets that combine a low emittance and large aperture.

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It is tentatively planned to have 32 straight sections in the ring for insertion devices, primarily undulators but a few wigglers to generate very short wavelength x-rays. And the bending magnets will continue to emit synchrotron light, which will also be exploited, as not all experiments will require the ultrahigh brightness of undulators.

Having an ultrahigh brightness x-ray beam from an undulator will also pose considerable challenges to accelerator operators and synchrotron light users. In a progress report delivered at the annual University of Wisconsin Synchrotron Radiation Center user's meeting in October, Knotek described beam lines leading from the ring to an experiment as having to be 40 to 50 meters long, partly because of the size of the ring and partly because of the heat dissipation problem. The x-ray beam will be only 1 millimeter in diameter at this distance. The position of the electron beam in the storage ring will therefore have to be exceptionally stable because, with this long lever arm, the slightest change in direction would be magnified and the radiation would miss the entrance slit of the experiment's optical system. Ground vibration that shakes the magnets and therefore the beam could be a problem, for example.

Heat poses a daunting threat of a different kind. Even with undulators, optical systems that can withstand the tremendous heat load have to be developed. Knotek mentioned the possibilty of three-stage monochromators, for example. The first would have refractory tungsten-carbon multilayer mirrors and dispersive elements to deal with the heat generated by radiation of wavelengths not passed on by the monochromator.

Researchers at the Ames meeting concluded that there are no overriding technical obstacles to building and operating the proposed x-ray source. "The demands are very exacting but are within the limits of existing technology," is the way Eisenberger described the situation to *Science*. However, considerable R&D prior to beginning construction is required. Miniworkshops held as part of the Ames meeting identified roughly $16 million of work to be done over 2 years in the areas of accelerator technology, insertion device research, and prototype beam line development. For construction to begin in fiscal 1988, which is the goal, about $6 million of this R&D would have to have made it into the fiscal 1986 budget, which is just about to be made public.

The tentative plan (pending approval by the funding agency that takes responsibility for the machine) concerning selection of the host laboratory for the x-ray facility differs from the traditional pattern in nuclear and high energy physics, where fully developed proposals from competing laboratories go head to head. Synchrotron researchers hope to forestall much of the bitterness accompanying this scenario by means of an early site selection, the end of this year being the present goal.

Proposals based on the "standard machine model" defined at the Ames meeting and refined at workshops of the steering committee would be received by the end of this summer. After selection of a site by the funding agency according to several criteria in addition to the technical design, the entire synchrotron radiation community would work together on a detailed construction proposal to be submitted for final approval.

All in all, synchrotron researchers have enough work cut out for them as it is, in going after the x-ray source. The focus in Washington on reducing the budget deficit and possible opposition by adherents of "small science" mean that they must have their technical and political acts even better put together than ordinarily.—**Arthur L. Robinson**

†"Synchrotron Radiation Source Research and Development," available from Materials Sciences Division, U.S. Department of Energy, Washington, D.C. 20545.