Pumping Out the

by SIDNEY PERKOWITZ

Research is thriving at Brookhaven's National Synchrotron Light Source.

LIGHT SOURCES FOR RESEARCH, which generate photons at high intensities, at unusual wavelengths, or under exquisite control, span a huge range in size. The smallest, those that produce a single photon, are essential if we are ever to understood the dual nature of light. The largest include lasers for thermonuclear fusion, such as the 500-foot National Ignition Facility recently proposed for Livermore; it would create conditions something like the early Big Bang inside a pellet of deuterium and tritium.

Equally impressive in its sheer massiveness, but designed for a different purpose, is a light source that has reached maturity during the last decade, the synchrotron. Its radiant power is not sufficient to emulate the early universe, but it is still enormous compared to other sources. And it comes with a bonus: unlike a laser, its power is emitted over much of the electromagnetic spectrum. Synchrotons offer a unique combination of high intensity and versatility; that is why those who use light as a research tool—from X rays to the far infrared—are flocking to these new sources.

The synchrotron is descended from the cyclotron that Ernest O. Lawrence developed at Berkeley in the 1930s to study atomic nuclei and elementary particles, beginning a line of machinery that has dominated these fields of research ever since. In a synchrotron light source, electrons enter a tunnel formed into a horizontal ring up to thousands of feet in circumference. They are held in orbit around the ring by strategically placed magnets, while they receive bursts of energy that bring them near the speed of light. As the energetic charged particles swing around the circle, they deform the electromagnetic lines of force that bind them to the rest of the Universe. That makes a cascade of radiation millions of times stronger than any

Photons

conventional source emits, covering wavelengths from the X-ray region to the infrared. This light emerges in an extremely narrow beam, so its full power can be delivered to a small area. And the light pulses on and off as each group of electrons circles the ring, like a great photographic flash unit blinking on a time scale of trillionths of a second.

This mighty source of photons illuminates the properties of solid matter, and of biological systems from molecules to organisms. Unlike elementary particle physics and space science, research in these areas has traditionally flourished at the small-scale, table-top level. Now individual researchers rely on these centralized light sources, a new kind of big science that enriches the meaning of a synchrotron facility. I have visited several, but know best the one where I ran experiments, the National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory, located on Long Island some 50 miles east of Manhattan.

When I returned there not long ago, I drove; but even from the air it is easy to pick out the synchrotron because its form so clearly follows its function. Its circular building echoes the huge ring around which electrons race to make X rays. Linked to that ring is a smaller but still large doughnut for ultraviolet and infrared light, where I ran my experiment. Its hangar-like enclosure has an industrial look—exposed girders, a crane to lift massive machinery, pitiless heavy-duty lighting. Mounds of research equipment fill the area around the ring with obscure shapes in stainless steel, festoons of electrical cabling, and flashing digital displays that embody data on the fly. This confusion is typical of a working laboratory, but the essential design of the synchrotron imposes an underlying order. The apparatus is arranged in clusters, each sitting at the end of a pipe—a beamline—from which photons

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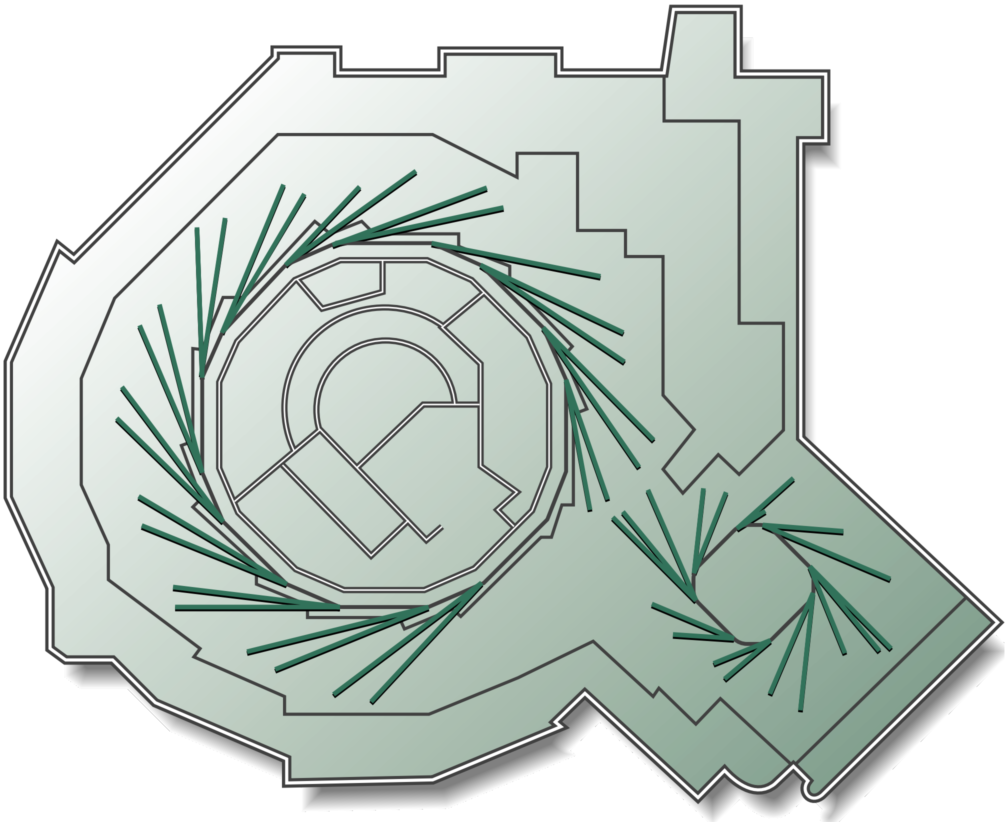

Layout of the beam lines at the National Synchrotron Light Source. Two electron storage rings feed X rays or vacuum ultraviolet radiation (VUV) to nearly 100 experimental stations.

emerge, like a farm field watered by an irrigation channel. Each beamline feeds experiments sponsored by a given institution or consortium. The result is one of the world's denser concentrations of scientific effort, with nearly a hundred research stations at the X-ray and ultraviolet rings.

In this surreal environment, it is comforting to see that each experiment is based in a human-scale lair fashioned from desks, chairs, computers, and racks of electronic gear. These dens surround the synchrotron like huts around a campfire, but the inhabitants are rarely visible among the thickets of equipment. Only traces appear—empty soft-drink cans, a chess board and pieces atop one cabinet, a toy pink flamingo peering down from another, a sign that pleads "Please don't feed the scientists." Any scientist sighted through the hanging electrical vines is likely to be a younger member of the species. Graduate students, and research associates just past their doctorate, do much of the day-to-day taking of data.

The synchrotron runs hard except when it must be closed for maintenance or modification, steadily pumping out photons to drive down their unit cost. Data may come at any hour of day or night, and it is never easy to get all the delicate equipment on a given beamline operating well at the same time. Motivation is strong to keep taking data as long as everything works. This accounts for the all-night atmosphere of crumpled soda cans and empty coffee cups that I could see especially well when I carried out research at NSLS, because my experimental station was located above the ring.

Apart from the demanding hours, the research floor is a difficult place to work, with its harsh lighting and ceaseless background noise. It is not that photons pop out of orbiting electrons with cracks of sound, like tiny lightning bolts with minute thunder. Photons are noiseless, even as they are created; lightning makes thunder only as it affects the air through which it flashes. But the synchrotron and the beamlines are evacuated, to keep air molecules from deflecting electrons and photons. The large mechanical pumps that maintain this emptiness produce the unpleasant noise. And always there is the knowledge that uncontrolled synchrotron radiation can be dangerous. Horns blare and lights flash every few hours when new electrons are about to be pumped into the ring, because that carries a danger of escaping radiation. Everyone leaves the research floor before any such "fill."

A view of the experimental floor at the NSLS VUV ring. (Courtesy Gwyn Williams, NSLS)

THE SYNCHROTRON is also a wonderful place to work. Its demanding aspects lend urgency and mystique to this huge enterprise of light, where research is at the cutting edge. The cheek-by-jowl conditions bring a remarkable cross-fertilization among scientists whose only common interest may be what light can do. When I ran my experiment there, I continually encountered friends and colleagues doing a variety of research within a few steps of my own station. Such interaction is a fruitful aspect of this particular brand of big science. To some extent, it eases older images of science as a lonely enterprise.

Among the hundred-odd beamlines, uses across scientific fields come thick and fast. Much of the work is fundamental, such as the effort in which I was involved—a study of one of the fascinating materials called superconductors. These have a seemingly magical property: when cooled to a certain temperature, they lose all electrical resistance, carrying current without losing any of its energy as heat. This happens in certain solids whose quantum rules permit cold electrons to march in lockstep like trained troops, rather than in chaotic motion like a fleeing crowd. The effect has been known since 1911, but its perfect efficiency never had a dream of commercial application because the necessary temperatures were impractically low, near absolute zero. In 1987, however, the physicists Johann George Bednorz and Karl Alex Müller, of the IBM Research Laboratory in Zurich, made an astonishing discovery that won them a Nobel Prize. They found a new class of "high-temperature" superconductors that lost resistance at much higher temperatures, still far below ordinary cold, but that could be easily reached by refrigeration. The discovery set off a worldwide scientific frenzy to understand and use these materials.

Our measurement was made to see if one of these complicated compounds, yttrium barium copper oxide (or YBCO, for short), obeyed the prevalent theory. This theory predicts that a superconductor has a gap in its energy levels somewhat like the band gap of a semiconductor. If the gap existed in YBCO, it would reveal its presence by absorbing certain infrared photons, as each type of semiconducting material absorbs characteristic wavelengths of visible or infrared light. But there was a problem; our sample was a thick slab of material that transmitted little light. Only the synchrotron provided enough infrared power to penetrate the sample, which enabled us to carry out the first such measurement ever made. Our data indeed

The NSLS VUV ring with its radiation shielding removed. (Courtesy Gwyn Williams, NSLS)

seemed to show the predicted light absorption, but with unexpected complications that make its interpretation uncertain. Despite this and many other efforts, the high-temperature superconductors remain puzzling. Infrared data, however, give important clues, and our results could not have been obtained without the high power of the synchrotron.

THE FACT that synchrotron radiation emerges in a narrow beam makes possible other unique research, such as the X-ray analysis carried out on a minute strand of the element bismuth, less than a hundredth the thickness of a human hair. Bismuth is interesting in its own right, for it is akin to both a semiconductor and a metal; but the value of this measurement was in establishing that the tiny filament was of crystalline form, making it probably the smallest crystal ever observed. Novel man-made materials, especially biological ones, are often made first in extremely small lots, which can be examined only by the fine beam of synchrotron light.

Other work at NSLS involves surface science, the study of how atoms and electrons behave at interfaces, such as that between the semiconductor silicon, and air or vacuum. The behavior deep inside a crystal is understood through its unrelentingly repetitive atomic geometry, but the regular array of atoms stops abruptly at the surface. This boundary region is difficult to describe, raising fundamental questions about surface behavior. The answers are significant for the semiconductor industry, where silicon chips must be made with pure surfaces before they can be turned into devices—and for industrial processes based on chemical reactions, such as the refining of oil and the manufacture of plastics. These depend on catalysts, compounds that accelerate chemical reactions without themselves changing. Many catalytic reactions occur best at interfaces; for instance, the catalytic converters used in automobiles contain platinum or palladium arranged with maximum surface area to clean polluting chemicals from the exhaust.

These industrial needs benefit from fundamental studies of surfaces. Whenever atoms of one type attach themselves to a surface of a different sort—say oxygen on silicon—they oscillate at specific frequencies that can be analyzed to determine their arrangement and linkages. The oscillations can be examined by infrared light—but at wavelengths, as it happens, where adequate sources have been in short supply until infrared synchrotron light became available. Other synchrotron studies use ultraviolet photons in a kind of photoelectric effect that drives electrons out of atoms at the surface to determine the electronic energies.

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And X rays from the synchrotron provide short wavelengths to resolve the geometric arrangement of surface atoms, just as they give structural details for solids.

Other efforts at NSLS are explicitly devoted to industrial technology. One is X-ray lithography, a means to pack silicon chips more densely with the intricate conduits that make up electronic circuits. The smaller these channels, the more devices can be crammed onto a piece of silicon. That march to smaller features has steadily increased the capacity of random-access memory chips for computers. But it is limited by the wave nature of light, which enters through photolithography, the technique that puts the pattern of channels onto the silicon. A wafer of silicon is coated with a light-sensitive chemical called photoresist. Light shines through a stencil or "mask" of the desired pattern, casting its image on the wafer. The exposed photoresist (for some types, the unexposed material) is easily removed, and the remaining chemical defines the pattern for further processing.

No matter how narrow the features in the mask, the width projected onto the silicon surface is affected by the illuminating wavelength. When light passes through an opening, it diffracts—that is, spreads out beyond the limits of the opening. The smaller the wavelength, the more photon-like the light, and the less the diffractive effect. With visible light, the features on a chip cannot be made smaller than half a micrometer across. That is only a tiny fraction of the width of a human hair, but as has been demonstrated at NSLS, short-wavelength X rays reduce the scale tenfold. This can translate into hundredfold gains in the density of electronic devices, and there are plans to standardize X-ray lithography for the semiconductor industry.

THE PATTERNS cut into silicon are complex, but biological patterns are even more so. Synchrotron light explores them in novel ways. Molecular biologists seek to understand the structural characteristics of molecules such as proteins, which determine their biological functions. X-ray and ultraviolet analysis can determine the positions of the atoms and how they are linked, but the data are not easy to come by for these large, intricate molecules. In pre-synchrotron times, X-ray data could not completely explain the structure of DNA, although they were the main clue that in 1953 led James Watson and Francis Crick to the double helix. Even later, in 1965, thousands of conventional X-ray images had to be assembled to give the first fully determined structure of an enzyme, one of the biochemical catalysts that accelerates the processes of life.

Such laborious analysis is speeded by the high power of the synchrotron, which reduces the time needed to obtain an X-ray image. And the harm X rays do to biological systems is minimized when the radiation comes in the short bursts inherent in the synchrotron. Compared to conventional methods, more data can be obtained before the sample deteriorates. This feature enters into a new research instrument, the X-ray microscope. It sees more finely than does a conventional visible-light microscope, for the same reason that X rays make finer lithographic patterns than does visible light. Because of diffraction, no detail smaller than the wavelength of the illuminating light can be seen. With visible light, the limit is half a micrometer or 500 nanometers. The intense but not too destructive short- wavelength X-rays at NSLS are the heart of a microscope that has discerned features down to 60 nanometers across in chromosomes, cells, and bone cartilage.

And the pulsed light of the synchrotron provides new views of biological behavior. It is molecular structure changing in time that leads to biological function. In the human eye, for instance, a change in shape of the molecule called rhodopsin—a tiny atomic gate swinging shut in response to an incoming photon—begins the act of interpreting light by the brain. Each rapid blink of synchrotron light can "freeze" a different configuration of a molecule. The changes in rhodopsin, and in the amino acids that comprise a protein, have been studied in this way. Ultraviolet synchrotron light has also

Aerial view of the National Synchrotron Light Source at Brookhaven National Laboratory.

by the time it reaches the coronary arteries, which degrades the image.

With X rays from the synchrotron, physicians can use the safer injection into a vein. The high power and the choice of wavelengths combine to give a clear image, with the patient receiving no more radiation than in the conventional method. Since 1990 patients have come with their physicians to NSLS. They are examined in a facility designed to minimize the inevitable reaction to this unorthodox approach. The treatment room resides at the end of a beamline, but one that has been separated from the main floor. The patient enters it without seeing the enormous machine whose light will soon penetrate his body. Still, the room is not especially comforting, but no worse than other medical technology we have all confronted. I myself would much rather occupy its patient's chair than enter again the tight tunnel of a massive MRI machine, where claustrophobia can approach panic proportions.

examined the shape of a protein occurring in the bacteria that causes Lyme disease, with its severe effects on heart, nervous system, and joints. The results elucidate how the body's immune system recognizes foreign organisms, a fundamental question whose answer may also aid in treating the disease.

Synchrotron light is more than a biological research tool. Clinical diagnostic medicine is also carried out at NSLS, in the coronary angiography project that uses synchrotron light to form images of the coronary arteries. These narrow conduits, no more than an eighth of an inch across, carry oxygenated blood to the heart muscle itself, with serious consequences if they become choked with fatty plaque. In the standard method of examination, a liquid that absorbs X rays is injected directly into the coronary arteries, through a long narrow tube called a catheter. This enhances a conventional X-ray image sufficiently to show the condition of the arteries, but the insertion of a catheter into a coronary artery has its hazards. The risk is lower if the high-contrast liquid is injected into a vein; then, however, it is diluted

That chair, resembling an old-fashioned barber chair, rests in line with the X-ray beam from the synchrotron. There the patient sits, after the high-contrast liquid has been injected into a vein. The members of the control and observation team work in an adjacent room, viewing the scene through glass that shields them from the radiation. They move the chair by remote control to briefly align the patient's heart with the beam. In a few minutes the image appears on a computer monitor, ready to be examined. Although the technique is highly promising, there is one worrisome aspect—what it would cost to build a single-purpose synchrotron devoted to clinical medicine. Improvements such as efficient magnets to control the electrons can reduce size and cost; but even a vastly scaled-down synchrotron is in the ten million dollar range.

DURING MY VISIT I spoke with Gwyn Williams of NSLS, who had provided the synchrotron expertise and equipment for our joint superconductor measurement. Like most working researchers, this mustachioed, British-born scientist was dressed casually, in jeans and running shoes. His devotion to the machine never flags, and he is always ready to talk about it, with such intense focus that he usually answered my question before I finished asking. He emphasized how young synchrotron science really is. NSLS has been running for over a decade, but it "takes ten years to get a synchrotron fully tuned up," he said. Improvements in this complex machine are still coming. Recently, for instance, it was noted that the beam of electrons wandered slightly as it dashed through the synchrotron tunnel. New controls have reduced this drifting, resulting in more stable light beams. Such improvements, along with novel approaches, are appearing in other designs. Synchrotron radiation laboratories, in fact, are springing up around the world—about forty, from proposed to operational, in fifteen countries. The newest in the United States include the Advanced Photon Source, whose ring two-thirds of a mile in circumference is located at the Argonne National Laboratory in Illinois; and the Advanced Light Source at the Lawrence Berkeley Laboratory, located in the same building that once housed a forerunner, one of the cyclotrons that Ernest Lawrence built.

That connection to a pioneering "atom-smashing" machine underlines an important theme in research with synchrotron light. In its earliest days, physics—and all science—was less differentiated than it is now. Only in our time has specialization reached the point where condensed-matter researchers, say, and elementary-particle physicists, seem to share precious little common ground. In a similar vein, "pure" and "applied" science and scientists often seem hardly to overlap. But although huge new accelerators have supplanted the synchrotron in cutting-edge elementary-particle research, this line of machinery has become essential for those who study living and nonliving matter at the level of atoms and molecules, crystals and biological cells; and for those who use light to develop electronic and photonic devices. The use of synchrotron light connects the table-top style of condensed matter research and biomedical science to the big-machine culture of high energy physics, and the societal impact of new devices to the philosophical purity of elementary particles—a subtle but significant contribution to the unity of science.