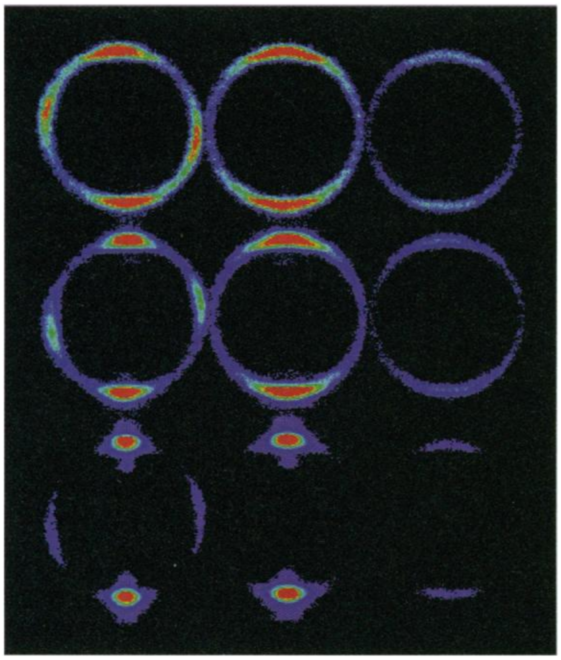
SCIENCE

Shining a Bright Light on Materials

In each of the world's three major regions of scientific influence—North America, Europe, and Japan—a powerful light has come on. The light sources are synchrotrons, race-track-like particle accelerators hundreds of meters across, and the light they shed is "hard," or high-energy, x-rays of unprecedented brilliance and purity. Researchers of all stripes who use x-rays to probe the structure of matter have come flocking to these "third-generation" light sources: the European Synchrotron Radiation Facility (ESRF) in Grenoble, France; the Advanced Photon Source at the Argonne National Laboratory in Argonne, Illinois; and Japan's Spring-8, which completed the trio this year. In this special news report, *Science* offers a tour of the ways in which these machines' unsurpassed beam quality and experimental conditions are opening new windows on everything from biomolecules and polymers to magnetic materials and Earth's core.



Following the news reports over the next seven pages, on page 1221 there begins a series of articles devoted to microstructural engineering of materials. The ability to observe microstructure in ever-increasing detail (such as the x-ray scattering images of a polymer undergoing shear, shown above), along with computational advances, provide insight into how material properties, such as strength and toughness, depend on structure. The articles outline strategies for using this understanding to improve materials.

A Special Report

The new facilities exploit a gift from nature that was long overlooked—even spurned. For decades following the realization early this century that x-rays could probe the structure of matter, researchers struggled with the feeble, poor-quality beams produced by x-ray tubes. Help eventually came from a quirk of particle accelerators first predicted by D. Ivarenko and I. Y. Pomeranchouk in 1944: As particles accelerate around a circle, they shed radiation.

The first visible synchrotron radiation was detected at General Electric's 70 MeV synchrotron in 1947. At that time, it was viewed not as an opportunity, but as a nuisance. Synchrotrons were designed for particle physicists, and the photons thrown off by the particles were an annoying energy leak; physicists had to keep pumping in more energy just to keep the particles going. When researchers finally studied this discarded radiation, they found that it had very appealing properties: It spans a broad spectrum from the far infrared to hard x-rays; it is pulsed and naturally polarized; and it is three to four orders of magnitude more brilliant than the beams from x-ray tubes.

In the mid-1960s, x-ray researchers began to camp out at high-energy physics labs. Like poor relations of the particle physicists, they would set up a few beamlines, parasitically extracting x-rays from the particle accelerators. By the middle of the 1970s, synchrotrons built specifically to provide x-rays began to appear, and the use of x-rays spread from physicists and chemists to materials scientists, geophysicists, and structural biologists. These synchrotron radiation sources—together with the neutron sources that were blossoming at the same time—were a new kind of facility aimed at multiple research communities consisting of thousands of users, who apply for beam time as they might apply for a grant.

Still, these second-generation synchrotron sources were largely based on the technology of particle physics: To generate the x-rays, they relied on the bending magnets that kept the beams moving in a circle. Researchers soon realized, however, that if they created more bends, they could make more x-rays. They began fitting second-generation sources with insertion devices, which use rows of magnets with alternating polarity to make the electron beam swerve back and forth, emitting x-rays with each turn. Insertion devices up the brilliance of the x-ray beam by another few orders of magnitude.

The third-generation sources, which began to come on line in the mid-1990s, rely almost entirely on insertion devices. The new sources come in two types: smaller ones that produce extreme ultraviolet and low-energy, or soft, x-rays; and giant, stadium-sized rings that generate high-energy, or hard, x-rays. The ESRF, for example, the first of the hard x-ray sources, is 844 meters in circumference and has 50 insertion devices positioned on straight sections of its electron storage ring. Not only do the devices increase the brilliance of the beam, but they also allow it to be tailored. Researchers can tune the wavelength of the x-rays, control their polarization, and choose between a single wavelength or a range of wavelengths. The high quality of the beam that emerges from insertion devices also makes x-ray optics—ingenious mirrors and "lenses" for focusing the hard-to-handle x-rays—much more effective. "You can play with the x-rays," says geophysicist Denis Andrault of the University of Paris.

With all these attributes, the new sources have taken researchers by storm. "The quality is spectacular," says solid-state chemist Kosmas Prassides of the University of Sussex in the United Kingdom. At the new machines, synchrotron users finally feel at home, says geophysicist Ho-kwang Mao of the Geophysical Laboratory of the Carnegie Institution of Washington in Washington, D.C. "First- and second-generation sources developed slowly and were not very friendly for users. All the instruments were together in an open space. It was very noisy and there was not much room. The third-generation sources are more user friendly. There is virtually unlimited space to build equipment around the beamline," says Mao. "Third-generation sources open up opportunities and open your eyes to new possibilities."

–Daniel Clery