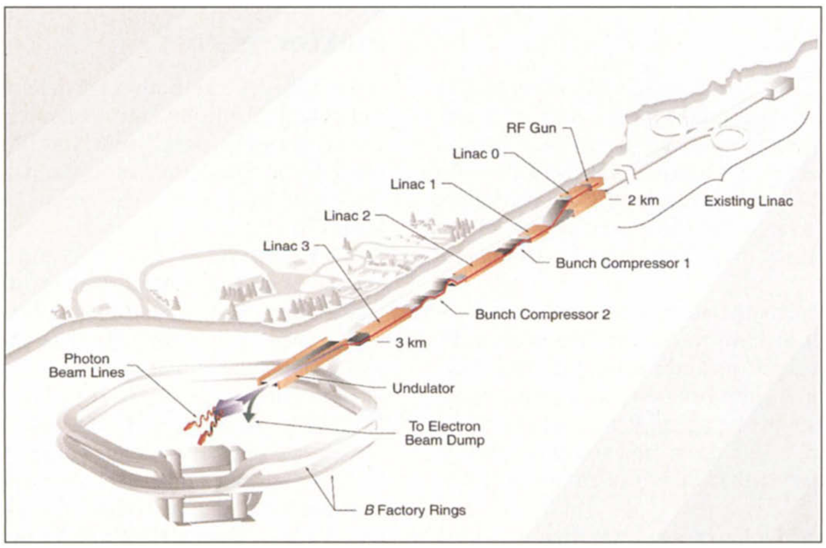
NEWS

Battle to Become the Next-Generation X-ray Source

For the first time in decades, researchers are looking past synchrotron storage rings for their x-ray future

It's crowded at the summit of x-ray science these days. Some 50 state-of-the-art x-ray facilities, called synchrotrons, dot the landscape worldwide. Another 20 are either under development or on the drawing boards. All are stadium-sized rings that produce bright beams of x-rays capable of the Superman-like feat of peering into the heart of matter to see the atomic structure of molecules. Together they've produced countless discoveries, ranging from atomic-scale maps of proteins that have been linked to disease to insights into the riddle of high-temperature superconductivity. But now, for the first time in decades, x-ray researchers have set their sights on new peaks that promise to raise their science to even loftier heights.

Researchers and science funding agencies are pondering a range of new x-ray sources, some of them add-ons to existing synchrotrons, others major new facilities in their own right. If built, these machines will generate much shorter x-ray pulses than top-of-the-line synchrotrons do today. Researchers hope to use those shorter pulses—possibly as short as 10 to 100 quadrillionths of a second, or femtoseconds—as ultrafast strobe lights to see not only the atomic structure of molecules but also the dance of atoms as they make and break chemical bonds. And one class of machines—called free electron lasers (FELs)—promises to give x-ray researchers something they have never had before: powerful beams of coherent high-energy x-rays. Like light waves from the laser at a supermarket checkout stand, coherent x-ray photons would travel together in perfect unison, rising and falling in lockstep. That regular behavior is expected to create x-ray beams billions of times more powerful than those available today, an accomplishment that could make it possible to collect entire data sets with just one blast of photons rather than the hours or days of beamtime needed today.



Next big thing? DOE must decide whether designs such as this add-on to the Stanford Linear Accelerator will make it off the drawing board.

CREDIT: SLAC

X-ray scientists insist that the new x-ray sources won't compete with one another. "The … facilities are complementary in terms of the science that can be done," says Roger Falcone, a physicist at the University of California, Berkeley. But because money is always tight, proponents will likely have to square off to persuade backers and funding agencies to support their projects. Still, no matter which camp scores first, researchers should gain access to x-ray beams unlike any seen before. "It's a very exciting time in pushing x-ray science into directions it hasn't been able to go to before," says Eric Rohlfing, who oversees atomic, molecular, and optical sciences research at the U.S. Department of Energy (DOE) office in Germantown, Maryland.

Stepchild to wunderkind

Not that the development of synchrotrons has been dull. The first synchrotrons were little more than particle accelerators built for high-energy physics experiments. Those accelerators whipped charged particles such as electrons to near light speed in giant ring-shaped machines and then smashed them into one another. Physicists then surveyed the wreckage for clues to the underlying structure of matter. But as electrons whip around storage rings, they shed x-rays, a side effect that causes them to lose speed. Particle physicists bemoaned that speed trap and tried to find ingenious ways to avoid it. But other researchers soon figured out that the x-rays could be useful in their own right. So they built second- and third-generation synchrotrons optimized to create far more powerful x-ray beams.

The problem, says Robert Schoenlein, a condensed matter physicist at Lawrence Berkeley National Laboratory in California, is that synchrotrons are somewhat inflexible when it comes to the length of the x-ray pulses they provide. A major reason is that when synchrotron operators inject packages of electrons into the storage ring, their primary goal is to keep them traveling and delivering x-rays to users for as long as possible. That means fiddling with the electrical charges as little as possible. One result, says Schoenlein, is that modern synchrotrons tend to produce trains of x-ray pulses each lasting tens to hundreds of picoseconds, and there is little that users can do to change that timing.

That might not sound like much time. But compared with the movement of electrons around an atom, it's an eternity. Trying to see the motion of electrons on that time scale is like trying to capture an image of a speeding bullet with an Instamatic camera: At best all you see is a blur. "Worldwide, there is a tremendous [interest] in being able to probe very fast time scales for very small structures," says Keith Hodgson, associate director of the Stanford Synchrotron Radiation Laboratory in Palo Alto, California. But because synchrotrons can't shorten their pulses, they aren't likely to take researchers where they want to go. "Conventional synchrotrons are near the end of the road," says Schoenlein. "To make major advances now will require new sources."

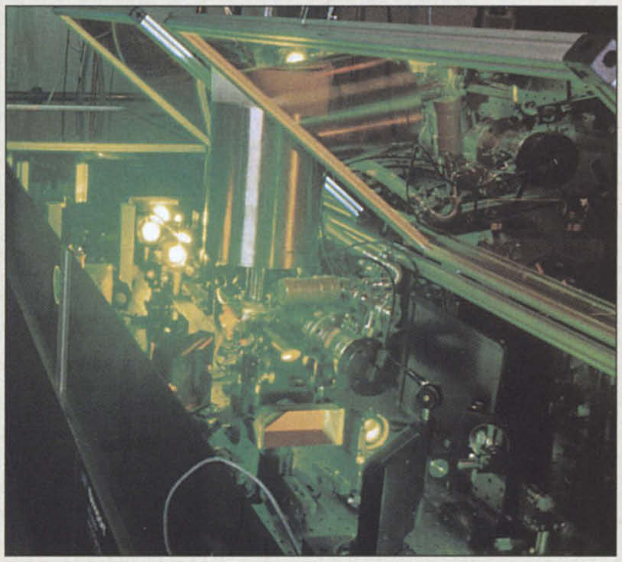
Four such sources are now vying for attention and funding. All are based on schemes for extracting x-rays from powerful particle accelerators, although researchers are also making steady progress in making x-ray beams from tabletop lasers (see sidebar).

The first is a synchrotron add-on called

High-Powered Short-Pulse X-ray Lasers: Coming Soon to a Tabletop Near You?

While researchers dream of turning energetic "hard" x-ray sources into ultrafast strobe lights, another class of machines—tabletop lasers—has been freezing fast action for years. Ahmed Zewail won the 1999 Nobel Prize in chemistry for using lasers with 200-femtosecond pulses to watch the breakup of isocyanide, among other chemical reactions. Femtosecond lasers have traditionally turned out photons of infrared light, a range of wavelengths that are far longer than those of x-rays and thus have a harder time spotting the motion of atoms. But researchers are continuing to make strides in developing femtosecond lasers that fire shorter wavelengths of light.

The first step was relatively easy: By simply shining infrared laser pulses through crystals capable of doubling the frequency of the light (thereby halving its wavelength), researchers produced laser light in the visible and even ultraviolet portions of the spectrum. But because such crystals absorb x-rays, other strategies have been needed to shorten the wavelengths even further.



Promising. Small, powerful short-pulse lasers could find a host of applications in science and industry.

Four years ago, laser physicists led by Margaret Murnane and Henry Kapteyn, then at the University of Michigan, Ann Arbor, reported that by firing infrared laser pulses into argon gas, they had ripped electrons off the argon atoms. The laser's oscillating electromagnetic wave carried these free electrons away from their parent atoms and then smashed the electrons back into the atoms, causing the atoms to emit soft x-rays (*Science*, 29 May 1998, p. 1412). Murnane and Kapteyn, now at the University of Colorado and JILA, a joint research institute of UC Boulder and the U.S. National Institute of Standards and Technology, and their colleagues refined the technique. In the 19 July issue of *Science* (p. 376), they reported that they had tuned the device to produce coherent light, all the photons marching together in quantum-mechanical lockstep. That coherence enabled them to use the short-pulse lasers to record high-density holographic data and should allow such lasers to be used for testing of advanced computer chip patterning components and possibly even developing a microscopic version of a computerized tomography scan, capable of imaging cells in exquisite detail.

Right now, Murnane and Kapteyn's technique is bumping against a wall. To turn out even more energetic hard x-rays, Kapteyn explains, researchers would need even higher powered lasers capable of carrying electrons away from ions and then smashing them back together with even more force. Unfortunately, such powerful beams scatter the ionized electrons like buckshot. "So you end up getting incoherent and dim emission," Kapteyn says. "On the other hand, to the extent that we can develop techniques to fix that problem, it's really not known what the potential of these techniques is to generate hard x-rays." In view of how quickly short-pulse lasers have developed so far, this dark-horse technique for generating hard x-rays is still very much in the race.

–R.F.S.

a slicing source. The approach uses an ultrafast laser to slice out a wedge of electrons from a pulse traveling through a synchrotron. This smaller slice of electrons then produces a shorter pulse of x-rays, possibly as short as 100 femtoseconds, says Falcone. Relative to the cost of a new facility, slicing is cheap. DOE is currently considering adding a slicing source to the Advanced Light Source in Berkeley, California, a project expected to cost about $5 million. The downside of the technique is that a slicing source discards most of the electrons in the original pulse. As a result, the x-ray beam it produces might be only a thousandth as strong as a typical synchrotron pulse.

Dimness won't be a problem with the Short Pulse Photon Source (SPPS), a separate add-on proposed for the Stanford Linear Accelerator Center (SLAC) in California. Instead of working with a ring-shaped synchrotron, SPPS is designed to make short pulses of x-rays from electrons fired down a straight-line linear accelerator, or linac. Like synchrotrons, linacs produce and accelerate intense short pulses of charged particles. Because researchers need not worry about keeping particle pulses stable for long periods, they can use a series of tricks to coax the electrons into creating shorter, denser bunches.

SPPS will turn these electron bunches into x-rays with the help of a common synchrotron device called a wiggler, a several-meter-long piece of equipment that houses an array of magnets with alternating polarity. As an electron beam hurtles through a wiggler, the alternating magnetic fields make it veer slightly back and forth, like a skier on a slalom course. With each turn the electrons shed x-rays, which by the end of the course pack as many as 100 million photons into a pulse lasting between 100 and 200 femtoseconds. Like slicing sources, the add-on is cheap; its expected price tag is just a few hundred thousand dollars.

SPPS has its limitations, though. When possible, x-ray researchers prefer "tunable" x-ray sources that let them choose the wavelength that works best for their experiments. But the x-rays SPPS spits out all have the same fixed energy level. What's more, it can fire only about 10 pulses a second, too few to capture more than one frame of a high-speed event. Even so, says Falcone, "it creates an intermediate solution for the field" between today's third-generation sources and a possible fourth-generation source dedicated to producing short pulses of x-rays of a tunable wavelength.

Bright futures

Topping the list of ideas for that fourth-generation source is an x-ray version of an FEL. FELs have been around for decades, but all of them built so far turn out longer wavelength photons, ranging from infrared down to ultraviolet. Getting an FEL to pro-

CREDIT: HENRY KAPTEYNE AND MARGARET MURNANE/JILA/UNIVERSITY OF COLORADO

duce the most energetic "hard" x-rays long seemed out of reach. But in the 1980s researchers discovered that—at least in theory—adding a 100-meter-long wigglerlike device called an undulator to a linac could create a tunable source of 200-femtosecond x-ray pulses. By manipulating the energy levels of electrons in the linac, operators can produce x-rays of different wavelengths. The long undulator also allows x-ray photons emitted by electron bunches to build up, stimulating the emission of still more x-rays—an advantage that not only makes the x-rays coherent but also creates beams up to 10 billion times brighter than those that top-of-the-line synchrotrons produce today (*Science*, 10 May, p. 1008).

X-ray experts are convinced that all that x-ray power would produce revolutionary science. Ultrabright x-rays, for example, might enable researchers to image the atomic structure of complex proteins without first coaxing millions of copies of the protein to line up in an orderly crystal, a requirement that's impossible to fulfill with many proteins today. "It's going to be qualitatively different in what you can do from a third-generation synchrotron," says Hodgson.

That potential has already enticed funding agencies in the United States and Germany to push ahead with x-ray FEL plans. At the DESY particle physics laboratory in Hamburg, Germany, for example, researchers are weighing plans to build an x-ray FEL alongside a proposed particle collider dubbed TESLA. Depending on whether the facilities share equipment and technology, the x-ray FEL could cost between \$470 million and \$700 million and could open its doors to users in 2010. U.S. officials, meanwhile, just approved \$6 million to draw up a detailed engineering design for the Linac Coherent Light Source (LCLS), an x-ray FEL designed to piggyback on SLAC. By using 1 kilometer of SLAC's existing 3-kilometer linac, LCLS could be built for as little as \$250 million. If funded and built on schedule, LCLS will open its doors in 2008, according to project coordinator and SLAC assistant director John Galayda.

Beyond FELs, one more shadowy range of x-ray peaks beckons researchers. A new class of machines called recirculating linacs is beginning to gain attention. "A recirculating linac is a hybrid between a linear accelerator and a storage ring," says the Berkeley Lab's Schoenlein. The machines also accelerate beams of charged particles and use them to produce x-rays. But instead of sending the electrons out in a straight line, as in a linac, or in a loop, as in a synchrotron, the machine forces them to spiral outward in a path resembling a paper clip (see figure below). In a unique twist, electrons traveling through successive spirals all swoop back through one common section of the accelerator. The design saves money by using the same equipment to give electrons multiple energy kicks. And as with a linac, the machine isn't a ring, so operators have the flexibility of manipulating the electron pulses to create ultrashort bursts of x-rays. "Nobody has prototyped one of these in the x-ray range," Hodgson says. "But it's really quite an exciting possibility."

Researchers in several groups have come up with recirculating linac schemes for compressing electron pulses as they travel, allowing them to turn out extremely short bursts of x-rays down to 100 femtoseconds and possibly even shorter. "That could potentially revolutionize some of the ultrafast x-ray work," says Stephen Leone, a physicist with a joint appointment at UC Berkeley and the Berkeley Lab, who chaired DOE's most recent advisory committee report on x-ray facilities. Early-stage proposals for building x-ray recirculating linacs are now being drawn up at the Daresbury Laboratory in Cheshire, U.K., and at Berkeley Lab and Cornell University in the United States.

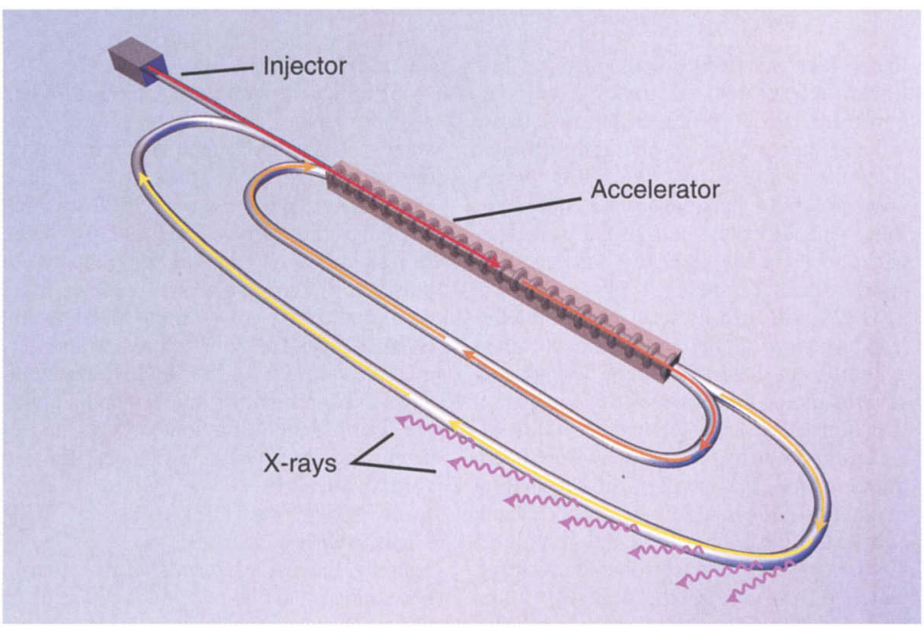
Just how all these proposals will sort themselves out remains to be determined. DOE's Basic Energy Sciences Advisory Committee is gearing up to set priorities for future x-ray choices. Their decision, expected next year, is likely to shape the landscape of x-ray science—both in the U.S. and in other countries whose plans depend on the course it follows—for decades to come.

–ROBERT F. SERVICE

X-RAY VISIONS: TODAY'S SYNCHROTRONS AND BEYOND

Machine	Photons per pulse	Pulse length	Pulses per second	Estimated cost
3rd-Generation Synchrotron	10^2–10^4	~10–160 ps	5.4 million	>\$1 billion
Slicing Source	10^3–10^4	~100 fs	10–10,000	\$5 million
Short-Pulse Photon Source	10^8	~100 fs	10	\$0.1 million to ?
Recirculating Linac	10^4–10^7	~100 fs	1000–10,000	\$300 million to \$500 million
Free Electron Laser (LCLS)	10^{11}–10^{12}	~200 fs	60–360	\$250 million

ps = picoseconds, or 10^{-12} seconds
fs = femtoseconds, or 10^{-15} seconds



Energy saver. Recirculating Linacs, such as this schematic layout based on designs from various laboratories, aim to provide ultrashort x-ray pulses with a smaller budget and footprint than today's synchrotrons. Electrons spiral outward as they gain energy.

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