

On the move. A Mars Exploration Rover checks out the local geology in an artist's dramatic version of the ideal landing site.

ipants found a full range of other safety concerns, from big rocks to steep slopes. More of a worry, perhaps, might be the uncertain scientific payoff in looking there for rocks altered in Mars's early warm and wet climate; at an early landing site workshop, only one scientist recommended Isidis as a site, whereas 14 voted for the hematite site.

At the end of this workshop, Gusev crater ended up a distant second to the hematite site. All agreed that Gusev held a deep lake early in Mars history, but many wondered out loud whether a rover on the crater floor—limited to its 600-meter roving range—would see anything more than a vast and vastly boring plain rather than the outcrops of exposed sediment layers that geologists yearn for. The accessible surface might even just be volcanic ash blown into the crater.

With Eos, Melas, and possibly Athabasca knocked out, Gusev and Isidis uncertain, and only the hematite site an apparent winner, participants left with plenty of work to do. Fortunately, project engineers had already convinced themselves that each spacecraft would have enough fuel to delay final commitment to specific landing sites until early next year. They also will be working on a system of small, horizontally firing rockets that could help the descending lander compensate for strong winds.

The geologists, reluctantly, are looking farther afield. "Hematite is still the favorite

by far," says Golombek, but he and others are considering four new possibilities, including ones that would exceed the latitude and elevation limits. The safest of the safe might be deep in Isidis basin where the European Beagle 2 lander is targeted, away from slope winds and rocks. "No one is very excited scientifically about" that area, says Golombek. More than once during the workshop, geologists called the Beagle site "boring" because it lacks an obvious scientific target. Planetary scientist Philip Christensen of Arizona State University in Tempe called it "crummy." He noted that less wind seems to mean more dust on the surface, and judging by surface brightness, which varies with the amount of dust, the interior of Isidis is dusty indeed. "You don't want to go there," he concluded.

But scientists will have to consider going to boring but safe places, if only to show NASA headquarters that going to scientifically exciting sites would be worth the risk. They'll also have to get more duct tape.

—RICHARD A. KERR

PHYSICS

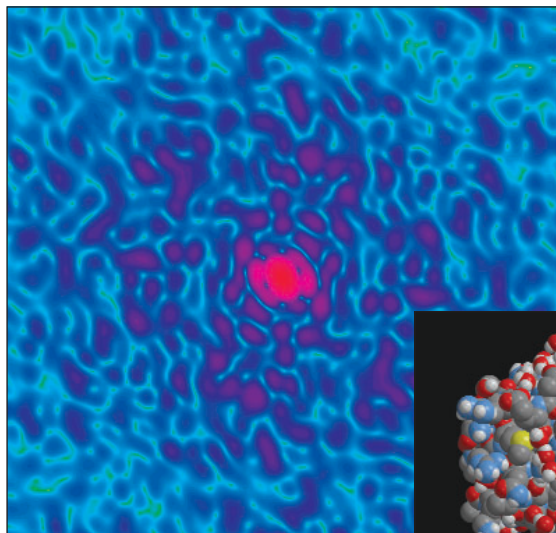
The Ultimate Bright Idea

Physicists think they can make an x-ray source 10 billion times brighter than today's best, opening new horizons in biology, chemistry, materials science, and physics. But to do it, they have to pull off a grand trick without mirrors

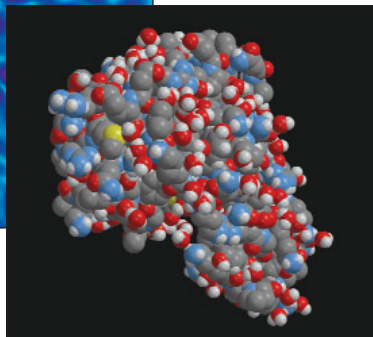
Some researchers are never satisfied with what they've got. In the past 2 decades, physicists have perfected the art of extracting intense beams of x-rays from synchrotrons—huge ring-shaped accelerators with circumferences of about a kilometer. Such synchrotron x-ray sources have revealed the structures of thousands of proteins, probed the intricacies of materials such as high-temperature superconductors, imaged tiny creatures only a millionth of a meter long, and advanced frontiers in a wide range of research fields. Yet even before they'd completed the latest synchrotrons, physicists dreamt of far brighter sources. Now, after a decade of planning, they are preparing to build their dream machines, x-ray sources 10 billion times brighter than synchrotrons. And to it make it possible, they're reinventing the laser.

The machines are known as x-ray free-electron lasers (X-FELs), and they promise to

reveal the structures of the most recalcitrant molecules, make movies of individual atoms bonding, and produce a state of matter similar to that found in the centers of planets. And that's just for starters, says physicist



X-ray portrait. Scattered X-FEL photons (simulated above) might enable researchers to reconstruct individual molecules such as this lysozyme (right).



Stephen Milton of Argonne National Laboratory in Illinois: "There will be revolutionary experiments that we haven't even dreamt up yet that will be done on such a machine."

An X-FEL is far from most people's image of a tabletop laser, however, so those dreams come with a hefty price tag. An X-FEL consists of a linear particle accelerator a kilometer or more long that produces an exquisitely groomed beam of electrons. The beam from the "linac" shoots through an elaborate 100-meter-long array of tightly spaced magnets called an undulator, the magnetic fields of which cause the electrons to move from side to side and emit x-ray photons (see figure, p. 1009). If the undulator and the electron beam are tuned just right, the photons and wriggling electrons will interact to generate an unprecedented blast of x-ray laser light. Building the entire rig from scratch could cost as much as a billion dollars, so two groups are looking for a way to put one together on the cheap.

Physicists at DESY, Germany's particle physics lab in Hamburg, plan to build an X-FEL alongside the lab's proposed particle physics collider, dubbed TESLA. By sharing parts and technology with the bigger machine, the DESY X-FEL should cost a relatively thrifty \$470 million and could start cranking

CREDITS: (TOP TO BOTTOM) JPL/NASA; DAVID VAN DER SPOEL; EDGAR WECKER/DESY

out x-rays for as many as 10 experiments in 2010. DESY researchers have demonstrated the basic principle in a test facility producing longer wavelength ultraviolet light. Physicists at the Stanford Linear Accelerator Center (SLAC) in Menlo Park, California, hope to be first off the starting blocks using an idle 1-kilometer stretch of the lab's existing 3-kilometer linac to build an X-FEL to serve four experiments. They hope to have the \$220 million machine running by 2008.

However, neither project is a done deal. DESY x-ray researchers are waiting for the German Science Council to give TESLA its blessing, says DESY's Jochen Schneider. "The government will come up with a decision at the end of 2003 or the beginning of 2004," he says, "and we don't know what they will tell us." The U.S. Department of Energy (DOE) has already committed to building SLAC's machine, but the agency has yet to give researchers the green light to start building. "They would like us to get started in 2005," says SLAC's John Galayda, "but the question is how big a start."

Look, ma, no mirrors!

Today's brightest x-ray sources, such as the European Synchrotron Radiation Facility in Grenoble, France, and the Advanced Photon Source at Argonne, wring x-rays from the electron beams circulating in synchrotrons. As a beam goes around, it emits photons much as a wet dishcloth flicks off drops of water if it is twirled from one end. To maximize the photon output, the electron beam runs through a series of undulators, each several meters long. Researchers have used the intense x-rays from synchrotrons to study matter ranging from cold viruses to molten iron under tremendous pressure. But experimenters would like still more intense and shorter pulses of x-rays, and synchrotrons cannot provide them because the bunches of electrons whirling inside them cannot be made sufficiently dense and short.

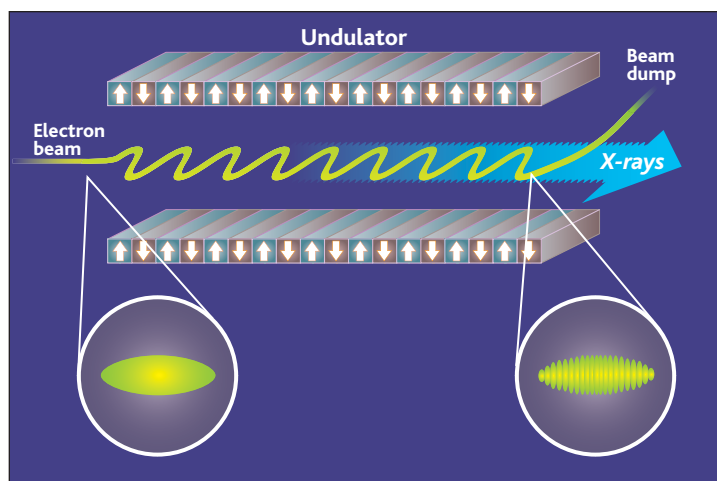
However, researchers believe they can obtain far brighter x-ray pulses with a clever rethink of a device called a free-electron laser, which was invented in the 1970s by John Madey and colleagues at Stanford University. Madey, now at the University of Hawaii, Manoa, showed that the photons produced in an undulator can induce the electrons to emit still more photons. Such "stimulated emission" is the key to making a laser. To do so, physicists place mirrors at each end of the undulator. These trap some

of the light so that it bounces back and forth, stimulating the production of more photons from subsequent bunches of electrons as they circulate through. Researchers already use free-electron lasers to produce beams of longer wavelength light. But for decades, an x-ray free-electron laser remained out of reach because it would require a very dense electron beam and because there are no simple workable mirrors for x-rays.

Then in the early 1980s physicists in Russia, Italy, and the United States figured out how to do away with the mirrors. Photons emitted in an undulator essentially travel along with the electrons, which are moving

thanks to the efforts of Richard Sheffield and colleagues at Los Alamos National Laboratory in New Mexico, who developed a better electron injector for linacs. The Los Alamos researchers placed a metal target inside an accelerator cavity and blasted it with a pulse of ordinary laser light. That kicked up a cloud of electrons, which was immediately sucked up into a dense beam by the accelerator before the like-charged electrons had a chance to push themselves apart. The result was dense, short pulses of electrons with less tendency to spread.

When researchers put these two technological advances together, they realized they could make a SASE x-ray laser out of a linac, says SLAC's Herman Winick. In 1992, he and colleagues at SLAC began planning to use the lab's existing linac as an X-FEL, which they dubbed the Linac Coherent Light Source. A year later, DESY physicists incorporated an X-FEL into their design for the TESLA collider. Since then, researchers at several laboratories have demonstrated SASE at longer ultraviolet wavelengths, and DESY researchers have even begun experiments with their SASE laser, which pumps out photons with wavelengths of 80 nanometers. Researchers in Japan, Italy, Germany, and the United Kingdom have also



All together now. In an X-FEL, accumulating photons herd electrons into microbunches that radiate in unison, hugely amplifying x-ray output.

very close to the speed of light. As the photons accumulate, they jostle the electrons, slowing those with slightly more energy and accelerating those with slightly less. If the undulator is very long, these interactions corral the electrons into a series of evenly spaced "microbunches" that move in synchrony and produce far more photons all moving in quantum-mechanical lockstep. Thus a wave of x-rays accumulates as the electrons make a single pass through the undulator.

Researchers dubbed the phenomenon "self-amplification of spontaneous emission"—abbreviated SASE and pronounced sassy—and Claudio Pellegrini of the University of California, Los Angeles, likens the harmonizing interplay between x-rays and electrons to the effects of a musical conductor on human voices. "Instead of a big room with everyone talking, you have a choir," he says. By coaxing the electrons to radiate in unison, SASE boosts the output of an undulator by a factor equal to the number of electrons in the beam—which can be as high as 10 billion.

But to make SASE work, researchers still needed much better electron beams. Those became available in the late 1980s,

proposed SASE machines that would produce longer wavelength soft x-rays.

A new scientific landscape

To justify building such a machine, researchers have been trying to predict what they'll be able to do with it. And although this wasn't entirely obvious at first, physicists now believe that an X-FEL will open entirely new fields of research, especially if they can get down to wavelengths of about a tenth of a nanometer and pulse durations of 1/10,000 of a nanosecond. "I think we will reach a new scientific landscape where no one has done experiments before," says DESY's Thomas Tschentscher.

For example, pulses of 1/10,000 of a nanosecond would be shorter than the time it takes for individual chemical bonds to change. Moreover, the x-rays could have wavelengths comparable to the lengths of such bonds. This should make it possible to study the activity of individual bonds within molecules, Tschentscher says. By taking stroboscopic snapshots of a molecule as it reacts to some stimulus, researchers could make a movie of its behavior.

The very short, intense bursts of x-rays

might also enable researchers to determine the structures of important but uncooperative biological molecules, says Janos Hajdu, an x-ray crystallographer at Uppsala University in Sweden. To determine a molecule's structure, researchers usually shine x-rays on a crystal; the multiple copies of the molecule produce a scatter pattern that reveals its shape. Some molecules, however, refuse to form large crystals. But a single blast from an X-FEL could shower a tiny sample—perhaps just a single molecule—with enough x-rays to reveal the molecular structure, just before it blows the sample to bits, Hajdu says. “It could allow you to use tiny samples because it is so intense,” he says, “and because it is so short, the atoms don't have time to move.”

X-rays from an X-FEL could also produce a state of matter similar to that found in centers of planets, called “warm condensed matter.” Such matter has the density of a solid but is heated to temperatures of about 10,000 kelvin, which are more typical of an ionized gas or plasma. The x-rays from an X-FEL could produce this type of matter by heating a sample so rapidly that it doesn't have time to expand. X-FEL studies of warm condensed matter should provide new data for astrophysicists studying planet formation and for engineers and physicists developing laser-induced nuclear fusion, says physicist Dick Lee of Lawrence Livermore National Laboratory in California.

For the moment, though, all these studies remain thought experiments, as researchers await the political and financial decisions that will determine when the first X-FELs shine. DESY's X-FEL, for example, is currently tied to the fate of TESLA, Europe's bid for the next international particle physics experiment after the Large Hadron Collider now under construction at CERN in Switzerland. Japanese and U.S. researchers are working on rival linac designs, and particle physicists worldwide will have to pick one before any money arrives (*Science*, 27 July 2001, p. 582).

But SLAC's Linac Coherent Light Source already has DOE's backing, says Patricia Dehmer, DOE's director of basic energy science. SLAC researchers should receive \$6 million in 2003 to plan the construction of the machine, she says, but “it's premature to say when it's going to be commissioned.”

Some researchers worry that in some regards the scientific potential of X-FELs is being oversold. For example, Richard Henderson, a structural biologist at Cambridge University, U.K., says that the first X-FELs won't be able to determine the structures of single molecules any better

than an electron microscope can when a sample is frozen to slow radiation damage. Henderson says that, overall, X-FELs have great potential and that one should be built. “But,” he says, “what you mustn't do when you're asking for a lot of money is overstate your case.”

And even x-ray physicists say there are still challenges to be met in building the machines. For example, to make an X-FEL work at wavelengths of a tenth of a nanometer, researchers must be able to control the position of the electron beam to within 20 micrometers over the entire length of the undulator, says DESY's Joerg Rossbach. They will also have to double the current in their beams while reducing

the beams' size and tendency to spread by a factor of 2. “We know how to do this,” Rossbach says, “because we understand the underlying mechanism and we understand the technology.”

Despite the scientific and political challenges, physicists are confident that their turbo-charged x-ray sources will be well worth the money and years of effort. “I personally believe it will be a revolution,” Rossbach says. And just maybe that will be enough to satisfy the physicists—at least until they come up with an even brighter idea.

—ADRIAN CHO

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MEETING EVOLUTION OF DEVELOPMENTAL DIVERSITY

Evo-Devo Devotees Eye Ocular Origins and More

COLD SPRING HARBOR LABORATORY, NEW YORK—From 17 to 21 April, evo-devo researchers met here for the Evolution of Developmental Diversity meeting to discuss how environment and quirks in development prompted the branching of the tree of life.

Did Eyes Come From Microbes?

In the mid-1990s, developmental biologist Walter Gehring came up with a heretical proposition: Eyes evolved only once. The idea was a hard sell. Because eyes are ubiquitous and come in vastly different varieties, most evolutionary biologists assumed that they arose independently many times. Now, Gehring has come up with an even more eye-popping suggestion: The original eye belonged to a microbe that later became a chloroplast, a sub-cellular center of photosynthesis best known for fueling growth in plants.

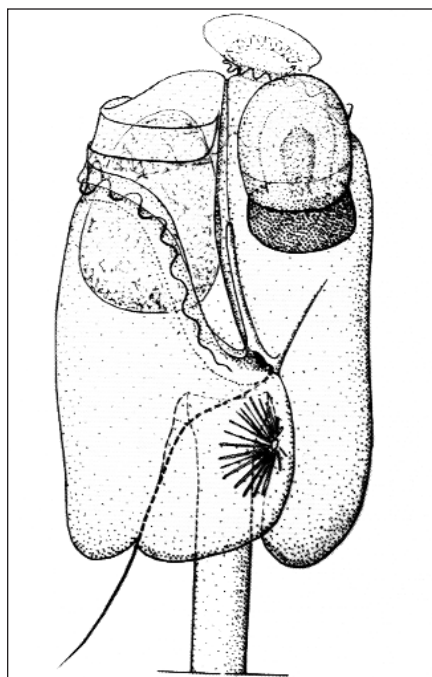
“It's a wild idea,” says Richard Behringer, a developmental biologist at the University of Texas M. D. Anderson Cancer Center in Houston. If true, “it would be fantas-

tic,” adds Nipam Patel, an evo-devo researcher at the University of Chicago. But he and others have their doubts.

At the meeting, Gehring of the University of Basel, Switzerland, described the thinking behind his new view of eye evolu-

tion. His proposal that eyes evolved only once rests on his 1995 discovery of a gene called *Pax-6* that is involved in eye formation in fruit flies, mice, and humans. Since then, he and others have been shaking the tree of life in search of more versions of this gene.

It has turned up in some 20 species; even primitive ones, such as sponges, have precursor versions of the gene. Each new find has convinced him that his proposition is correct. However, the notion remains controversial—indeed, it met with



Eye to eye. This schematic of the eye of an obscure species of dinoflagellate reveals a complexity akin to that of our own eyes.

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