Femtosecond Pulses Help Physicists Go to Extremes
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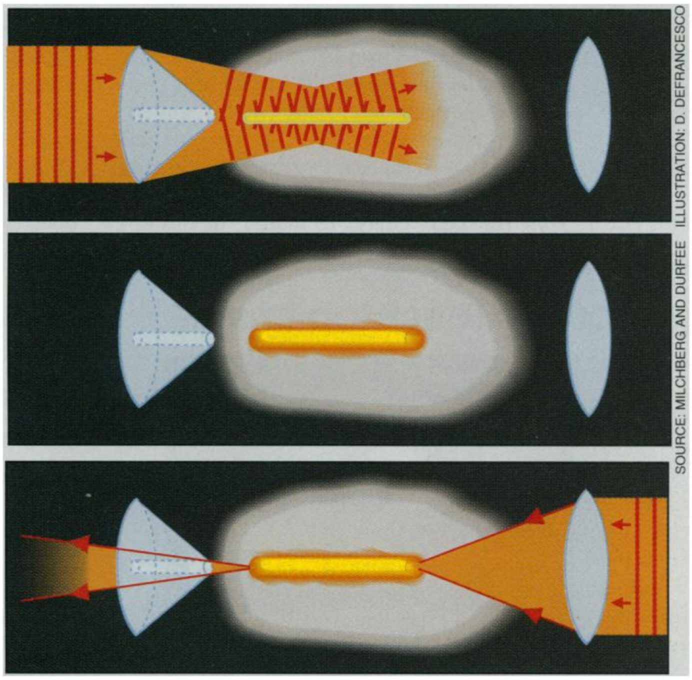
LASER PHYSICS

Femtosecond Pulses Help Physicists Go to Extremes

Physicists have known for centuries that one of the surest ways to make new discoveries is to go to extremes: shorter timescales, greater intensities, higher energies, smaller distances. Going to extremes isn't easy, or cheap. Frequently it forces researchers to turn to ever larger and more expensive facilities: miles-long particle accelerators, massive fusion test-beds, radiotelescope arrays spread over counties. Until recently, laser physicists also found their tools getting bigger and more expensive as they reached for more intense laser beams. The most intense beams came from the largest lasers, such as the $176 million, 24,000-square-foot Nova facility at Lawrence Livermore National Laboratory.

But brighter no longer has to mean bigger. A new generation of compact, relatively inexpensive lasers is generating light at intensities that surpass those of even the largest present-day laser facilities. These new lasers sit on modest optical benches and draw current from standard lab outlets. While Nova can pack 40 kilojoules of energy into a pulse, the total output of a typical short-pulse laser (SPL) may be just 50 millijoules—nearly a million times less. But thanks to techniques developed in the mid-1980s, that output can be squeezed into a pulse lasting just 150 femtoseconds, or quadrillionths of a second (see sidebar). Focused down to a 3-micron spot, a pulse that short can reach intensities 100 times that of Nova: 10^{18} watts per square centimeter. Those unprecedented intensities are enabling researchers to turn gases into media with entirely new optical and electromagnetic properties.



SOURCE: MILCHBERG AND DURFEE ILLUSTRATION: D. DEFRANCESCO

Blazing a trail. An intense laser pulse, refracted through a special lens, creates a tube of plasma that can channel a second pulse.

What are these novel effects? By ripping the electrons away from the atoms along its path, a pulse from an SPL creates a trail of ionization that can channel subsequent laser beams like an optical fiber. At the same time, the freed electrons in this plasma vibrate at relativistic speeds, generating radiation at many times the frequency of the original beam. That mechanism and others can turn the plasma into a powerful source of x-rays for, say, imaging biological samples. And in another effect now being harnessed, the electrons in the plasma experience a so-called ponderomotive force, as the high average velocity of electrons in the region of intense light causes them to behave like a hot gas and expand outward.

Such effects "allow people to test in the lab ideas that seemed very farfetched," says Chan Joshi of the University of California, Los Angeles, who is working to harness the ponderomotive effect in a compact particle accelerator. And SPLs have a key advantage over monsters like Nova, says Howard Milchberg of the University of Maryland, College Park. "To get anything done [at large laser facilities] you had to have a committee meeting. Freewheeling science couldn't be done. With these things, you come in in the morning, get a cup of coffee, do an experiment, and if you don't like it, you get another cup of coffee and do another experiment before lunch."

Keeping a beam on track

For all their benefits, though, SPLs come with their own distinct challenges. One is the difficulty of handling such intense beams. Tightly focused pulses from an SPL ordinarily spread out quickly and lose their potency, often within tens of microns. With lower-powered lasers, the solution to beam spreading is to channel the light in an optical fiber. That approach won't work here, though, because the pulse from an SPL would destroy any known optical fiber. Milchberg and his graduate student Charles Durfee have been working on a solution: using one pulse from an SPL to create a tiny tube of plasma that can channel a second pulse for long distances. Says Milchberg, "We're beating the Rayleigh length"—the distance an unchanneled beam would travel.

In this scheme, the initial pulse is fired into a gas through a special lens called an axicon. The axicon redirects the beam and causes it to interfere with itself, creating a line of peak intensity extending out from the lens. A tube of plasma forms along the high-intensity region, and a shock wave expands through the plasma and hollows out the tube, creating a channel of greatly reduced plasma density. The second pulse (focused with a standard lens) is fired right down the channel. The walls of the channel refract the pulse back and forth, containing it.

So far, the experiment has channeled beams of 10^{14} watts per square centimeter for a distance of 2.5 centimeters. That may not sound like much, but it is 70 times the Rayleigh length in that system. If the method works at higher intensities, says Phillip Sprangle of the Naval Research Laboratory, it could be "very attractive" for SPL-based schemes that require long propagation, such as particle accelerators and x-ray sources.

Since SPLs are so attractive, it's no surprise that others are working on ways to channel their intense beams. One is Charles Rhodes of the University of Illinois, Chicago. Rhodes finds that if the SPL beam is sufficiently intense—10,000 times more intense than those Milchberg works with—the light actually confines itself. Together, Rhodes has found, the ponderomotive force and the electrons' relativistic jitter raise the plasma's index of refraction—and the increase is greatest along the axis of the beam. The resulting refractive-index gradient tends to confine the light to the beam axis. The effect is that of a light pipe created by the light itself.

One expert calls Rhodes' experiment "almost surreal." Rhodes himself says he wasn't sure it would work until he saw a computer analysis of the interaction between the pulse and the plasma by some Russian colleagues. Looking through the computer plots, he says, "was like turning on the lights in a dark room."

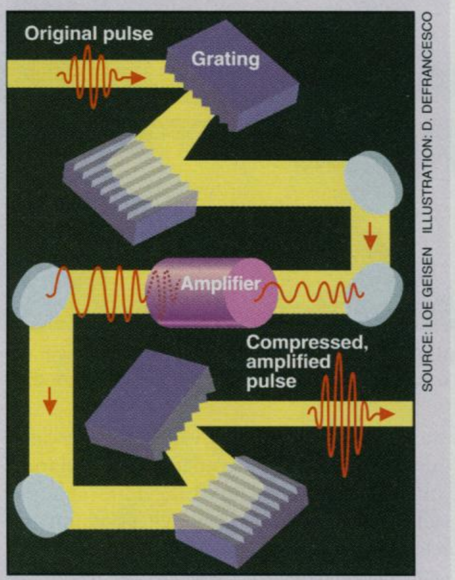
Rhodes is putting this effect, called laser self-focusing, to work in a scheme for converting a plasma into a source of intense, coherent x-rays—an x-ray laser. The starting point is a gas made of clusters of rare-gas atoms ionized by a blast from an SPL. The electrons torn away from the clusters focus the pulse and enable it to create a longer trail of plasma. Meanwhile, other electrons, freed from individual atoms but still locked inside the clusters, rattle around and drive the cluster atoms into highly excited states. These atoms can release their energy quickly, in a burst of x-rays—an effect Rhodes has already observed. But by exciting clusters in a sufficiently long plasma, Rhodes hopes to generate a coherent laser beam of x-rays.

Rhodes thinks his x-ray laser could eventually yield billion-watt bursts of coherent x-rays lasting a picosecond, or trillionth of a second—intense and fast enough to record detailed, three-dimensional x-ray images of living cells before the radiation destroys them. Traditional sources of x-rays, such as massive synchrotron facilities, simply can't match those intensities, Rhodes says. And although a jolt from Nova can also turn a plasma into an x-ray laser, the resulting x-ray pulses are too long-lasting for this application. Fortunately, Rhodes says, SPLs let you "do some jujitsu on the physics," relying on their extremely short pulses for the leverage to surpass brute-force methods.

Indeed, the prospect of turning SPLs into compact sources of pulsed, very bright x-rays has lured a number of other SPL researchers, each with his own method. Roger Falcone of the University of California, Berkeley, and his co-workers are training their SPL on metallic solids. As electrons torn loose by the pulse recombine with metal ions, the vaporized solids emit incoherent, subpicosecond bursts of x-rays, creating an x-ray source that, though less intense than Rhodes,' would be simpler and even more compact, and could serve as a probe of material surfaces. And Sprangle hopes to use his lab's SPL as the centerpiece of a powerful source of picosecond x-ray pulses that would be both tunable and coherent. He envisions scattering laser pulses off an electron beam from a compact accelerator. Like baseballs hurled at an oncoming train, the laser pulses would gain energy from the electron beam, jacking up their frequency into the x-ray realm. By adjusting the electrons' energy, investigators could tune the x-ray energy to match the absorption spectrum of, say, calcium—an important regulator of cell activity—and localize it in the cell with unprecedented resolution.

A Bigger Bang From a Benchtop Laser

What laser fits on a tabletop yet delivers a pulse more intense than would result if the entire electrical output of the United States were channeled into a laser beam a centimeter wide? The answer: a short-pulse laser (SPL). These paradoxical devices, which are transforming fields such as x-ray optics and particle acceleration (see main text), are based on a simple trick: taking a small power output and packing it into a pulse lasting only trillionths or quadrillionths of a second.



SOURCE: LOE GEISEN ILLUSTRATION: D. DEFRANCESCO

The long and short of it. In chirped-pulse amplification, a short laser pulse is stretched before it is amplified, then squeezed back down afterward.

As a starting point, an SPL generates a laser pulse that can have virtually any intensity and power, providing it includes small amounts of spiky noise, like the crackles on a loudspeaker. With a set of techniques generally referred to as mode-locking, the hardware in an SPL filters out everything but the shortest noise spikes, converting the beam into isolated short pulses. One mode-locking technique uses what is called a saturable absorber: a dye or other medium that absorbs light only up to a certain amplitude, letting the peaks pass through. Each short pulse can then be re-boosted in a second laser amplifier.

The intensity can be pushed up only so far, however, without blowing the optics. To overcome this limit, many SPLs rely on a technique called chirped-pulse amplification (CPA), first applied to solid-state lasers in 1985 by Gérard Mourou, now director of the Center for Ultrafast Optical Science at the University of Michigan, and Donna Strickland, now at Princeton University. CPA stretches short pulses in time by bouncing them off an optical grating, amplifies these longer, less intense pulses, and then uses another grating to squeeze them down again almost to their original length. That way, intensities can be pushed up many times higher than before, and a puny tabletop laser can deliver a knockout punch.

–J.G.

Making waves with an SPL

Such mini-synchrotrons aren't the only SPL-based schemes for shrinking traditionally huge facilities. Another is the laser wakefield accelerator, conceived by John Dawson of UCLA in 1970. Conventional steel and concrete accelerators have an inherent limitation: The electric fields that accelerate the particles can be made only so strong without tearing electrons from the machine's components, destroying it. As a result, physicists wanting to study particles at higher energies have had to resort to ever larger and more expensive machines, culminating in the (now defunct) Superconducting Super Collider. Dawson thought he saw a way out of the dilemma: Create the accelerating fields in a plasma, where the fields can be as strong as you like because there's no structure to tear apart. Higher electric fields, in turn, should open the way to a more compact accelerator.

Dawson envisioned blasting a plasma with extremely intense light pulses lasting about a picosecond. Each pulse would shove the plasma electrons aside through the ponderomotive force, forming an electrostatic wake containing tremendous electric fields. Charged particles dumped into the wake would be accelerated to high energies in a relatively short distance.

When Dawson first proposed this scheme, says Joshi, "people almost laughed." The laser requirements—far shorter, more intense laser pulses than were then available—seemed outlandish. To make up for the lack of picosecond lasers, Dawson proposed a variant called the beat-wave accelerator, in which two longer laser pulses interfere to create a series of intensity peaks, simulating a series of shorter pulses. Several investigators, including Joshi, have tested the beat-wave scheme with encouraging results. And now, with the availability of true short-pulse lasers, Joshi and other investigators are starting to test Dawson's original scheme.

The spate of mini-synchrotrons and mini-accelerators spawned by SPLs makes it clear that small labs will be among the major beneficiaries of the technology. But Dawson cautions against making predictions about where SPLs will make their biggest mark. It may come, he says, in areas of physics that for all practical purposes don't exist yet. With the short x-ray bursts generated by an SPL, for example, "you could take moving pictures of molecular motion" or probe the dynamics of atomic electrons on timescales that are now completely out of reach. Says Dawson, "Where all this will go is anybody's guess."

–James Glanz

James Glanz is a science writer in Chicago.