Taking Short-Pulse Laser Energy to New Peaks

It is an extraordinary accomplishment in itself—a tabletop laser system that delivers ultrashort pulses with a peak power of 100 trillion watts, each lasting 400 quadrillionths of a second. But the contribution of this new 100-terawatt (TW) laser, whose power is equal to our Nova laser's for a fraction of the time, is that it is a stepping stone to the Laboratory's quadrillion-watt (petawatt) laser system, which is scheduled for completion late this year. The 100-TW system will help us perform preliminary tests of certain concepts and components that we hope to investigate later on the petawatt laser. One such concept is that of the fast ignitor, a promising method for achieving fusion ignition at lower laser energy than was previously thought possible. Confirmation of this concept might hasten the day when controlled inertial confinement fusion will be used for commercial power production.

How the System Works

The 100-TW system has two main sections (see the figure below). The pulsed beam is formed in the first section, a 1.5- × 6.6-m tabletop laser setup in a separate room adjacent to the Nova laser. The beam is piped to the second section, a target bay that is also fed by two of Nova's ten beams. (The 100-TW system uses a few Nova components in the target bay—most notably the two-beam target chamber itself—but it can operate either independently of Nova or in conjunction with it.)

Solid-state amplifier materials, such as titanium-doped sapphire (Ti:sapphire) and neodymium-doped glass (Nd:glass), make it possible to extract several joules of energy from modest-scale laser systems. Ti:sapphire also makes the energy gain available over the large wavelength range that is needed to amplify pulses lasting less than a picosecond (1 ps = 10^{-12} s, or a trillionth of a second). However, all amplifier materials have nonlinear components in their indexes of refraction; that is, they bend the light path by degrees that vary with the intensity of the beam. Because of this nonlinearity, intense beams tend to self-focus destructively. We must therefore limit the beam's intensity (the energy in the pulse per unit of area *and of time*) within amplifiers. One way to decrease the intensity is to make the area very large. Nova decreases intensity by expanding the beam diameter to 74 cm through its amplifier chain. However, the intensity of subpicoseconds pulses would remain too high even if the beam were spread to a Nova-size diameter. Therefore, we must increase the pulse duration in order to decrease the energy per unit of time.

To alter the pulse duration, we use the technique of chirped pulse amplification. We stretch the duration of the pulse before amplification and then compress it back down to approximately its original duration after amplification. In a chirped pulse, the frequency of the laser pulse changes throughout the pulse. By delaying the frequencies late in the pulse, we can stretch a short pulse into a long one. By delaying the frequencies early in the pulse, we can compress a long, broad-bandwidth pulse into a short one. Diffraction gratings separate different frequencies, send them in different directions, and vary their delays. In a pulse stretcher, sending the higher frequency (blue) light over a longer path than the lower-frequency (red) light stretches out the pulse. (Diffraction gratings are described in the article beginning on p. 24 of this issue.)

Following the Pulse

In the case of our 100-TW laser, a commercial Ti:sapphire oscillator produces 0.1-ps pulses with energies at the nanojoule level—short pulses at low energy. As indicated in the figure below, we stretch their duration to 3000 ps—a factor of 30,000. Then, we amplify the stretched pulses with a linear regenerative amplifier using Ti:sapphire. The pulse enters the linear amplifier at 10 to 100 picojoules (pJ), makes about 130 passes through it, and comes out at approximately 7 millijoules (mJ). This is an amplification of a billion—a huge portion of the total energy gain needed to produce 100 TW of power.

At 7 mJ, the intensity is getting high enough that self-focusing can occur in the Ti:sapphire crystal. Having pushed this limit in the first amplifier, we expand the beam in diameter to lower its intensity without decreasing its energy and send it into a second Ti:sapphire amplifier, a regenerative ring amplifier. The 7-mJ beam makes approximately 15 round-trips and is amplified to about 60 mJ.

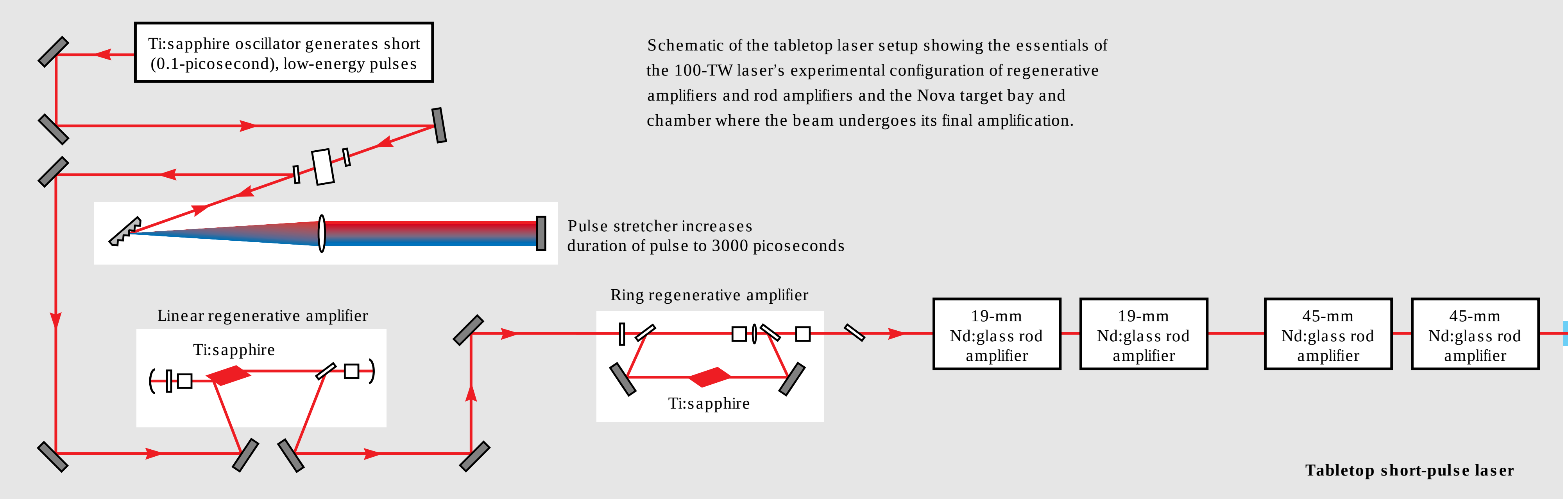
At this point, we have amplified the beam as far as is practical in Ti:sapphire and have maintained its bandwidth (frequency range). We must then use two pairs of Nd:glass amplifiers for higher energy extraction. The first pair are 19 mm in diameter, the second are 45 mm. The beam is expanded in diameter at each stage to maintain a reasonably low intensity. To maximize the efficiency of these amplifiers, we clip the edges off the beam, giving it a "top hat" or rectangular crossectional profile. Clipping the beam halves its energy to about 25 mJ. The first pair of rod amplifiers increases the energy to 2 J and the second pair to 15 J. This beam is then piped from the tabletop setup to the two-beam target bay in Nova.

In the target bay, the beam undergoes its final amplification. Passage through a standard 9.4-cm-diameter Nova disk amplifier brings the beam energy to about 60 J—a fivefold gain. The beam passes through a spatial filter, is expanded to about 14 cm in diameter, and enters the pulse compressor. The two 40.6-cm-diameter gold diffraction gratings (see photo on p. 36) within the compressor undo the stretching that we did at the beginning (these Laboratory-designed and -made gratings are superior to commercial gratings both in wavefront quality and damage threshold). Delaying the red light more than the blue compresses the pulse from 3000 ps to about 0.4 ps. We cannot achieve full compression to the original 0.1 ps because of the narrowing of the pulse spectrum in the glass rod and disk amplifiers.

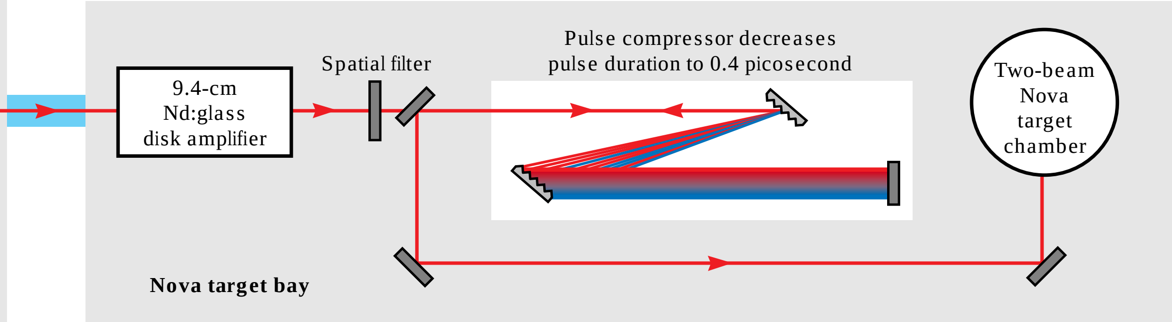
The beam loses some energy on the gratings and mirrors in the compressor and comes out at about 40 J. The beam enters the target chamber, where it is focused by an off-axis parabolic mirror from 14 cm in diameter to a 10-micrometer (μm) spot, yielding an intensity of 100 quadrillion watts of power per square centimeter (10^{20} W/cm^2) when it strikes its target, higher than any short-pulse system has ever achieved.

The Uses of Short, Intense Pulses

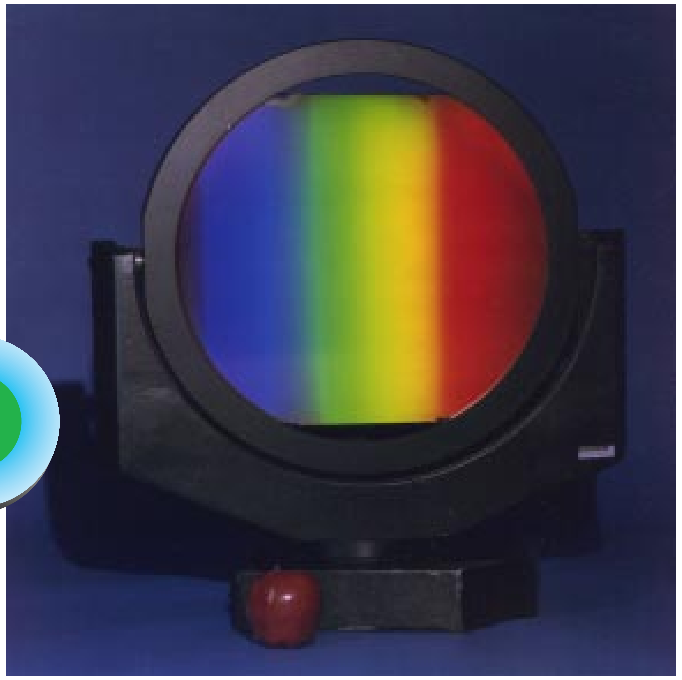
The ultrashort pulses and extremely high intensities of the 100-TW laser will enable us to advance our understanding of laser–matter interactions. A pulse of high-density light impinging on a solid surface drives an ultrahigh-pressure shock wave into the material. Studies of the propagation of such strong shocks can provide information on the fundamental properties



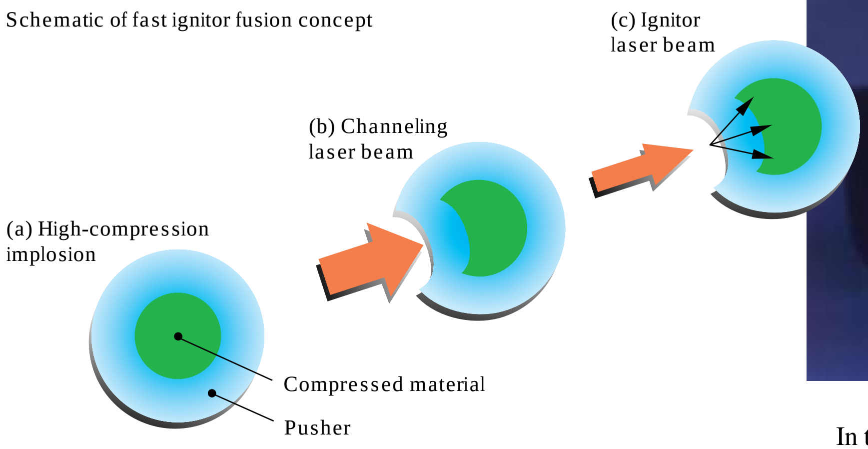
Schematic of the tabletop laser setup showing the essentials of the 100-TW laser's experimental configuration of regenerative amplifiers and rod amplifiers and the Nova target bay and chamber where the beam undergoes its final amplification.



One of the two gold gratings in the compressor chamber of the Nova target bay. These gratings return the stretched pulse to about 0.4 picoseconds in duration before it enters the Nova target chamber.



Schematic of fast ignitor fusion concept



of matter—for example, the equation of state of a material, investigation of which is particularly important to the Laboratory’s science-based stockpile stewardship work. These studies promise to further our understanding of how pressure is developed in a given material when a given amount of energy is added to it—that is, its equation of state, which is the thermodynamic relationship between the energy content of a given mass of material and its pressure, temperature, and volume.

The electric field of our 100-TW, 0.4-ps laser is many orders of magnitude larger than the fields that bind electrons within the atoms of the target material. A near-instantaneous liberation of a large number of outer-shell electrons from those atoms can create a highly charged plasma or “gas” of electrons or ions. The plasma is “cold” because there is no time during the picosecond pulse for the ions or electrons to interact and thermalize. Cold plasmas are ideally suited to test the concepts on which certain x-ray laser schemes are based.

Fast Ignitor

The Laboratory’s 100-TW facility provides us with our first tools to begin to address the fast ignitor fusion concept, which requires extremely high powers on the order of a petawatt (10^{15} W). Focusing a high-power laser pulse gives rise to an extremely high density of energy, or light pressure. When a pulse of high-density light impinges on a solid surface, an ultrahigh-pressure shock wave can be driven into the material. These intense pulses also generate large amounts of energetic (about a megaelectron-volt) electrons. These high-intensity phenomena form the basis of the fast ignitor fusion concept.

In the fast ignitor scheme (see schematic at left), laser energy compresses a spherical volume of fusion fuel to high density—exactly as in the conventional approach to inertial confinement fusion. However, in the conventional approach, the fuel must be compressed to the point that it ignites. By contrast, the fast ignitor concept will add two laser beams to the fusion process. The first, a channel beam made up of 100-ps pulses, bores through the plasma created by the conventional laser driver and pushes the fuel in its path toward a higher density near the core of the fuel. The second, an ignitor beam, interacts with this density gradient and generates hot, high-energy electrons that penetrate the core and instantaneously raise its temperature, hastening ignition. The relation between conventional fusion ignition and the fast ignitor concept is roughly analogous to the relation between the diesel engine and the gasoline engine: the diesel uses compression ratios of about 100:1 to ignite the fuel in the absence of a spark; the typical gasoline engine uses a spark to ignite its fuel at a compression ratio of about 10:1. The fast ignitor technique, if proven successful, will not only offer the advantage of circumventing the rather difficult task of ignition by compression alone but also promises fusion gain at significantly less input laser energy than in conventional inertial confinement fusion.

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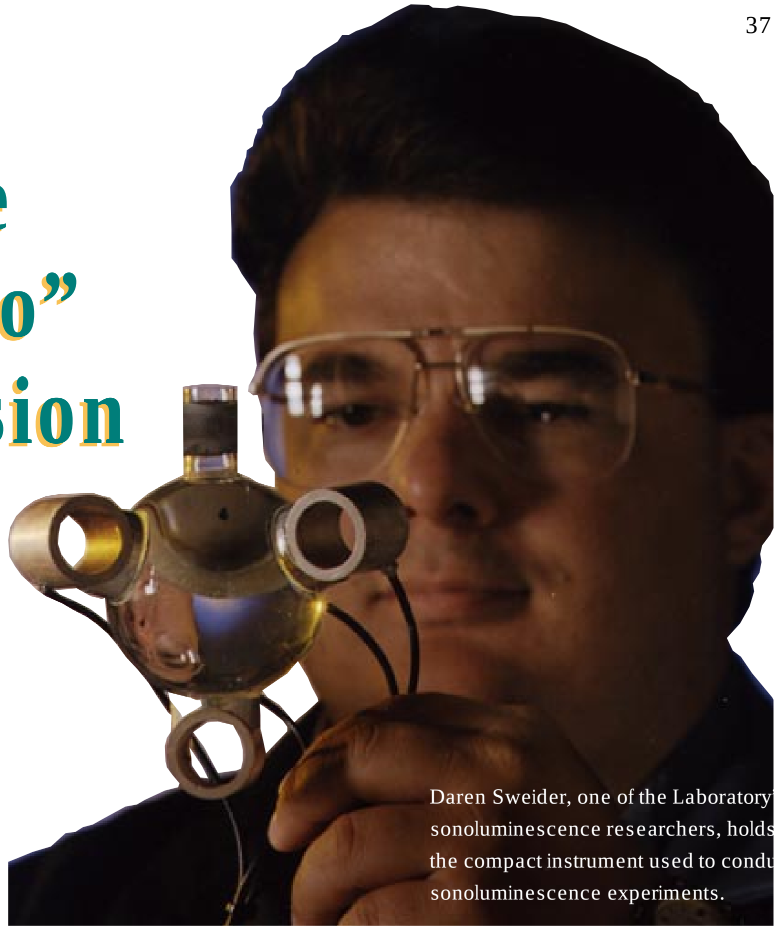
Sonoluminescence and Tabletop “Micro” Thermonuclear Fusion



Daren Sweider, one of the Laboratory’
sonoluminescence researchers, holds
the compact instrument used to condu
sonoluminescence experiments.

SONOLUMINESCENCE is the curious phenomenon of converting acoustic energy to optical energy—literally, turning sound into light. Although first observed more than 60 years ago, only recently have we begun to understand the phenomenon. We know that the light observed does not result from the acoustic field directly; rather, it results from a process called cavitation, in which gas-filled bubbles in a liquid form, grow, and collapse in response to the pressure waves generated by the sound pulses; as the bubbles collapse, they compress or implode and heat the gas to the point that it emits light.

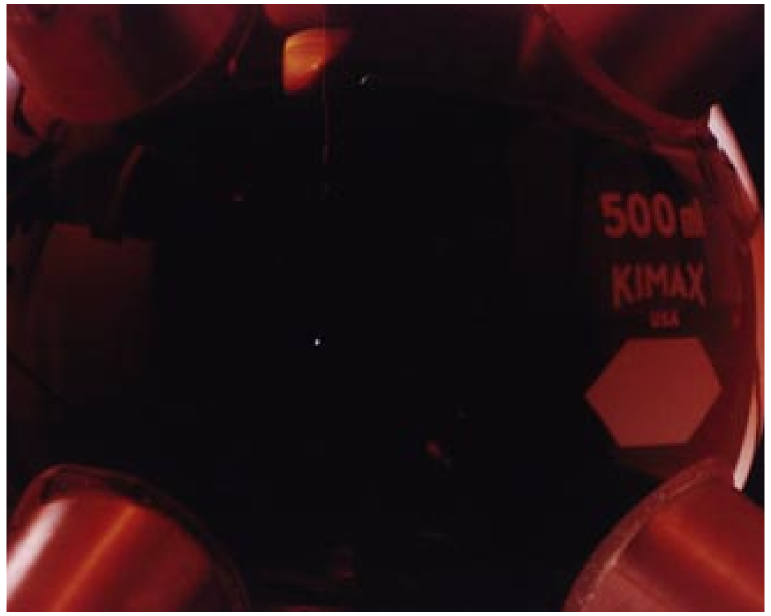
Scientists at Lawrence Livermore National Laboratory have been investigating the physics of implosions experimentally and calculationally for more than 40 years, first for nuclear weapons and then for inertial confinement fusion. These fusion studies previously involved nuclear detonations or massive laser systems. Imagine the savings and advances possible if tabletop sonoluminescence systems could generate the pressures and temperatures necessary to study nuclear fusion. Today, Livermore researchers are pursuing such possibilities using complex numerical models to investigate the effects of spherical convergence on the dynamics of bubbles. These are the same numerical models developed initially to simulate the implosion phase of nuclear weapons. The results of sonoluminescence simulations reveal the underlying physics of the phenomenon. What is especially intriguing about spherical convergence as related to sonoluminescence is the realization that it happens so intensely, yet nondestructively, in a tabletop experiment (see the photograph on p. 38).

Many Bubbles vs One Bubble

The first observation of sonoluminescence was recorded in 1934 by H. Frenzel and H. Schultes, of the University of Cologne, who found that photographic plates submerged in a water bath and irradiated with ultrasonic waves became exposed. The early research that followed concentrated on the random growth and collapse of large numbers of cavitation bubbles and involved fairly general analyses of a cavitation field containing many bubbles of various sizes. The analyses were helpful in uncovering gross aspects of sonoluminescence but did not reveal much about the physics of the individual cavitation events or the resulting bursts of light.

In 1990, D. Felipe Gaitan, now at the Jet Propulsion Laboratory in Pasadena, and Lawrence A. Crum, now at the University of Washington, discovered the conditions under which a single bubble could be trapped in water in a flask and made to stably expand and contract and emit light synchronously with the applied sound pulses. They found that an acoustic field equivalent to about 110 decibels is required to trap a bubble and cause it to expand and contract. This sound intensity is comparable to that of a smoke detector alarm held an inch or so from one’s ear, but the frequency of the sound is beyond the range of human hearing. The Gaitan method, which involves carefully tuning both the amplitude and the frequency of the acoustic field, provided a simple and inexpensive experimental setup for studying sonoluminescence in detail.

A year later, researchers at the University of California at Los Angeles, headed by Seth Putterman, applied the Gaitan method to determine the duration of the sonoluminescence flashes and the flash-to-flash interval. Studying, in Putterman’s words, this “hydrogen atom of sonoluminescence,” they found that each light pulse lasts less than 50 picoseconds (1 ps = 10^{-12} s) and that the time between flashes was extremely stable and nearly synchronous with the frequency of the sound pulse. In addition, measurements of the spectrum of emitted light indicated



Single-bubble sonoluminescence. A single, stable bubble (visible near the center of the photograph) oscillates about an equilibrium radius of a few micrometers, expanding and contracting and emitting light each acoustic cycle.

extremely high temperatures—at least several tens of thousands of degrees.

Previous explanations of sonoluminescence could not account for the extremely short pulses of light or the high temperatures. The calculations by Livermore scientists, however, provide the best explanation to date of the origin of both by showing that a spherically converging shock wave, generated within the collapsing bubble by the acoustic pulse, creates a relatively high energy density at the center of the bubble.

Simulations at LLNL

Beginning in 1992, a group of Livermore researchers performed numerical simulations to study the hydrodynamics that govern the growth and collapse of an air bubble in water. Unlike previous simulations done elsewhere, they treated both air and water as compressible fluids. These simulations showed that the acoustically driven compression is nearly isentropic until the final 10 nanoseconds (1 ns = 10^{-9} s). During this very brief time, strong spherically converging shock waves evolve in the bubble (see the graph on p. 39). As a result, the central region heats to very high temperatures—about 350,000 kelvin (K), or 30 electron volts (eV)—and emits light. Reflection of the shock from the center of the bubble produces a diverging shock wave. The subsequent flow behind the shock wave quenches the high temperatures and pressures—and thus the light pulses—in a few picoseconds.

These data are consistent with Putterman's measurements. In addition, the calculated temperatures for an air bubble in water are only one or two orders of magnitude lower than the ten-million-degree temperatures required to fuse deuterium.

Laboratory researchers then simulated the growth and collapse of a bubble containing pure deuterium (an isotope of hydrogen) and one containing a mixture of deuterium and water vapor containing deuterium. In this simulation, they found that pure deuterium in deuterated water alone cannot exhibit picosecond sonoluminescence because the speed of sound in deuterium is too rapid to sustain a shock in the collapsing bubble. However, because the bubble actually contains pure deuterium plus deuterated water vapor, the sound speed is lowered so that the mixture can support a sustainable shock. When the contents of the bubble are modeled as this mixture, calculated temperatures and pulse widths are consistent with preliminary experimental data collected at Livermore—that is, measured pulse widths of less than 15 ps and violet light emissions, corresponding to temperatures of a few electron volts (30,000–40,000 K).

Agreement between the deuterium-plus-vapor simulations and experimental data provides a starting point for examining practical methods to enhance an implosion. Many parameters can be varied, including the size and composition of the flask, the composition of the liquid, the size of the bubble, the ambient temperature and pressure, and the characteristics of the applied acoustical field. To minimize the perturbations to the "standard" sonoluminescing system, the Livermore researchers first studied the effect of "shaping" the acoustical pulses.

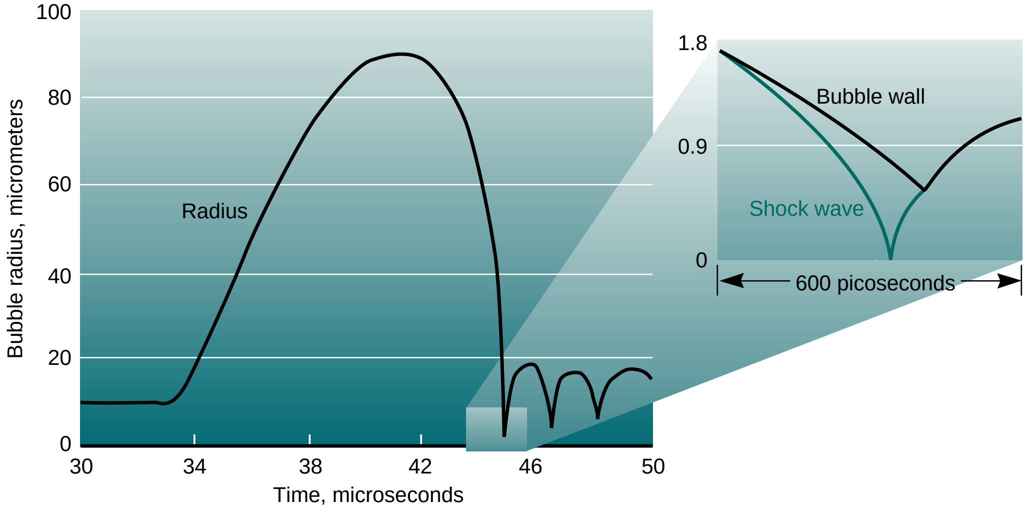
Spiking the Field

For another simulation using deuterium bubbles, they hypothesized that an acoustic "spike" of pressure, superimposed on the sinusoidal drive, would enhance the implosion by supplying extra energy without affecting the mechanisms that allow sonoluminescence to occur. Sonoluminescence is known to be extremely sensitive to the overall system acoustics that result from the periodic driving wave generated by the applied pulse. The preliminary experimental data show that deuterium bubbles are indeed brighter when the driving acoustical field has a spike.

Calculations reveal that a peak central temperature exceeding 500 eV (5.8 million K) may occur for a modest spike. The spike greatly accelerates the liquid–gas interface early in the implosion. Because acceleration occurs early in the implosion, there is ample time and distance for spherical convergence to increase the amplitude of the shock greatly and, therefore, the pressure and temperature in the center of the bubble.

It must be noted, however, that because these calculations currently do not include radiant energy transport and thermal conduction, the calculated pressure and temperature increases may be somewhat overestimated. Despite this simplification, fusion of the deuterium may occur under these intense pressure and temperature conditions.

Deuterium fusion produces neutrons. An estimate of the number of neutrons produced is 0.1 neutron per hour, neglecting the unrealistically high calculated temperatures at the very center of the bubble. Although this count rate is low, it should be measurable. Because neutron production is coincident with the flashes of light, the arrival of neutrons at the detector can be determined accurately. In addition, the energy spectrum of fusion neutrons is well defined. Thus, by temporal and energy gating (a mechanism similar to a camera shutter), most of the spurious background signals can be removed, making it possible to accurately detect fusion neutrons produced from sonoluminescence.



A graphic simulation of the bubble wall over time during a growth and collapse cycle. The enlarged area shows the critical time when the shock wave slams into the center of the bubble and light is emitted, indicating high implosion temperatures and pressures.

Fusion from Sound

At least theoretically, tabletop fusion appears possible. The numerical simulations done at the Laboratory provide the foundation for a serious attempt to attain thermonuclear fusion from a sonoluminescencing bubble. They indidcate that under specific, extreme experimental conditions, such as those simulated at Livermore, a very slow but scientifically interesting reaction rate is possible.

The Livermore numerical simulations also show many ways to improve the experimental results. For example, the neutron production rate can be increased by at least a factor of 50 if the deuterium is replaced by a mixture of deuterium and tritium. Modifications of the spike amplitude, timing, and shape may provide further enhancements. Raising the ambient pressure of the system to increase the bubble mass could be another enhancement.

Sonoluminescence experiments to date have produced light emissions lasting less than 50 picoseconds. Calculations indicate that single-bubble sonoluminescence may result in temperatures of near 1000 eV (more than 11 million K), pressures greater than 10 million atmospheres, and mechanical energy concentrations of up to 12 orders of magnitude. Further calculations and more sophisticated experiments are needed to demonstrate the feasibility of producing tabletop "micro" thermonuclear fusion.

The Livermore researchers caution that this approach offers no shortcuts to achieving fusion. Rather, it is a clever idea for doing some of the same physics that the Laboratory's Nova laser does but on a much smaller scale and at a relatively low cost. At the very least, applying the spiked driving pressure to any sonoluminescing system may provide the general scientific community with easy and inexpensive access to pressures, temperatures, and time scales that have been unattainable previously.

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