Progress in Laser Fusion

Infrared laser beams, converted to shorter wavelengths by optical crystals, may heat heavy hydrogen to 100 million degrees Celsius. Recent work suggests the technique could lead to useful fusion power

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In the past year four of the world's largest laser systems, the NOVA laser at the Lawrence Livermore National Laboratory in Berkeley, the GEKKO-XII laser at the University of Osaka in Japan, the PHEBUS laser at Limeil, France, and the OMEGA laser in our laboratory at the University of Rochester, have come into operation at visible and ultraviolet wavelengths. At the Los Alamos National Laboratory another kind of laser, operating at a slightly shorter ultraviolet wavelength, is under development. Many large laser systems play an undisputed role in weapons research and development. Nevertheless, the lines of scientific investigation opened up by all these instruments make it possible to be guardedly optimistic about an outstanding peacetime benefit: the scientific feasibility of harnessing fusion power by laser may well be demonstrated in the next 10 years.

Major advances in two disciplines are primarily responsible for this optimism. In optics a phenomenon called harmonic-frequency conversion has been exploited to generate high-powered laser beams that have a much shorter wavelength than was previously possible. The advance is significant because laser energy can be transferred to a fusion fuel pellet much more efficiently at short wavelengths than it can at long wavelengths.

In computer modeling the simulation of fusion reactions initiated by lasers in fuel pellets has become increasingly detailed and realistic. Simulations now make it possible to specify quite accurately the characteristics of fuel pellets and incident laser beams that are needed to generate economically viable fusion power. Moreover, remarkable instrumentation can now trace the evolution of the fusion reactions to within a hundredth of a nanosecond. (A nanosecond is a billionth of a second.)

The controlled release of the energy derived from the fusion of atomic nuclei has been one of the fondest hopes of science since the potential benefits of the process were recognized and serious work on it was begun nearly 40 years ago. It is well known that a mixture of deuterium and tritium, the heavy isotopes of hydrogen, makes the most suitable fuel for fusion. The basic scientific objective is to heat ions of deuterium and tritium to sufficiently high temperatures and maintain the temperatures long enough to realize a net energy gain from the fusion of the ions. In each fusion reaction a deuterium ion and a tritium ion give rise to an alpha particle, or helium nucleus, and a neutron; the total kinetic energy released, which is shared by the two reaction products, is 17.6 million electron volts.

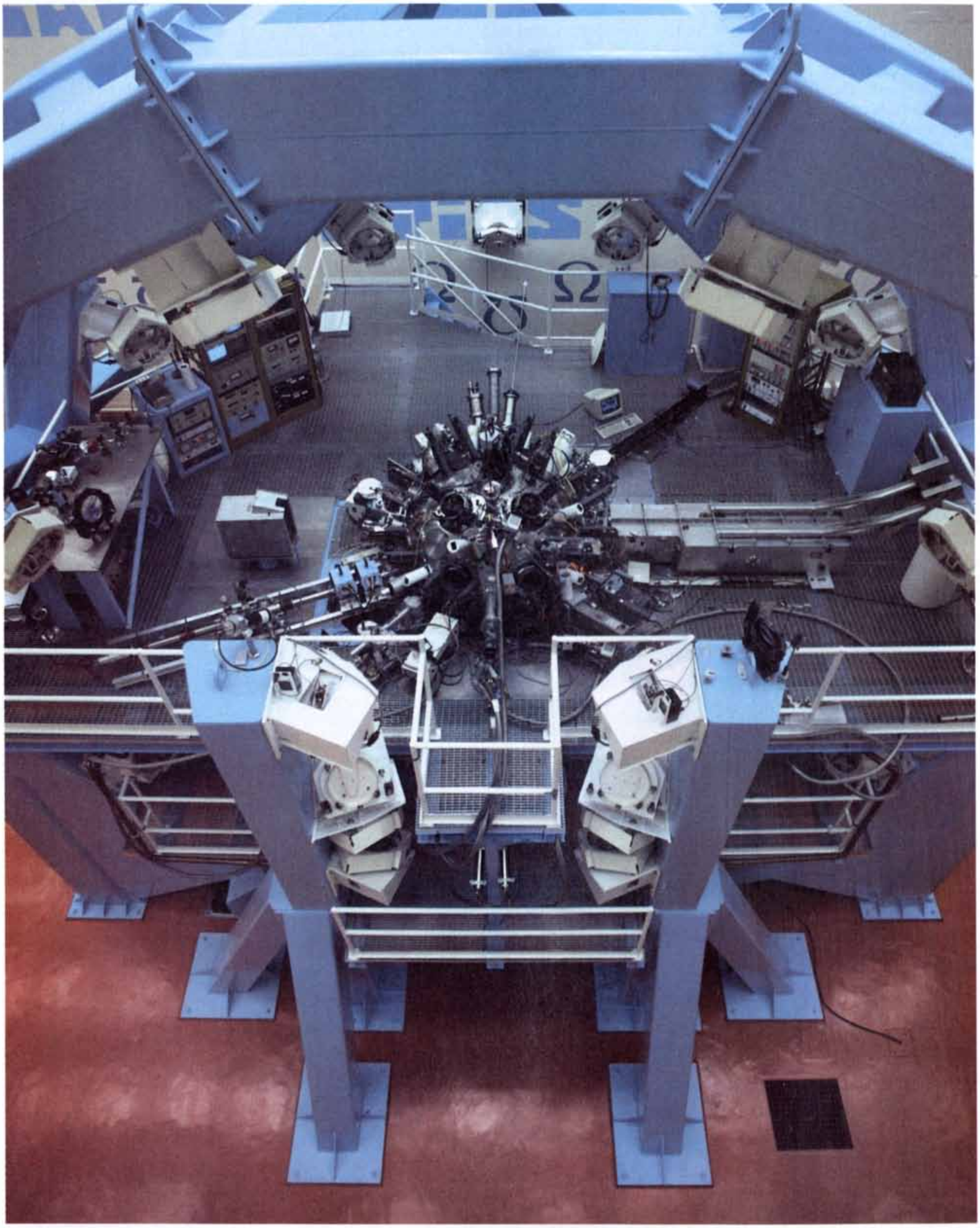
In the long term, fusion between deuterium ions alone could provide a practically limitless source of energy, since vast quantities of deuterium are available from seawater. For example, the energy from the fusion of the deuterium in a pool of water 100 feet on each side and seven feet deep could satisfy the electrical energy needs of the city of Rochester for a year.

Laser Fusion

The best-known scheme for creating the conditions needed for fusion has been to heat a plasma, a hot, electrically neutral gas of ions and free electrons, that is confined by a strong magnetic field [see "The Engineering of Magnetic Fusion Reactors," by Robert W. Conn; SCIENTIFIC AMERICAN, October, 1983]. In the early 1970's, however, workers in the U.S. began experiments on a radically different method of heating and confining a plasma, one that exploits the extraordinary heating potential of the laser [see "Fusion by Laser," by Moshe J. Lubin and Arthur P. Fraas, SCIENTIFIC AMERICAN, June, 1971, and "Fusion Power by Laser Implosion," by John L. Emmett, John Nuckolls and Lowell Wood, SCIENTIFIC AMERICAN, June, 1974]. A beam or pulse of laser light is split into several smaller beams of equal intensity. The split beams are amplified in energy and subsequently brought back together by a system of mirrors and lenses; the beams are thereby focused on a small region from different directions. A charge of deuterium and tritium fuel is encased in a spherical shell a few millimeters in diameter, made of plastic, glass or some other material, and the resulting fuel pellet is placed at the intersection of the beams; the pellet is thus uniformly illuminated.

The laser pulse almost instantly ionizes the atoms in the outermost layer of the pellet, but the material inside a certain critical radius is opaque to the laser energy. Incident energy is consequently absorbed in a dense layer of plasma that surrounds the deuterium-tritium fuel. The heated layer of plasma expands and ablates, or becomes explosively torn free, from the rest of the pellet; the velocity of the ablated plasma is typically 1,000 kilometers per second. An equal and opposite force accelerates the material inside the ablation layer inward, in accordance with Newton's third law, as if it were a rocket propelled by the plasma escaping all around it. The concentric implosive force is sufficient to accelerate the remaining shell to a velocity of several hundred kilometers per second in a billionth of a second. The radius of the fuel is compressed as much as 50 times, and the resulting high temperature and high density of the fuel cause it to fuse.

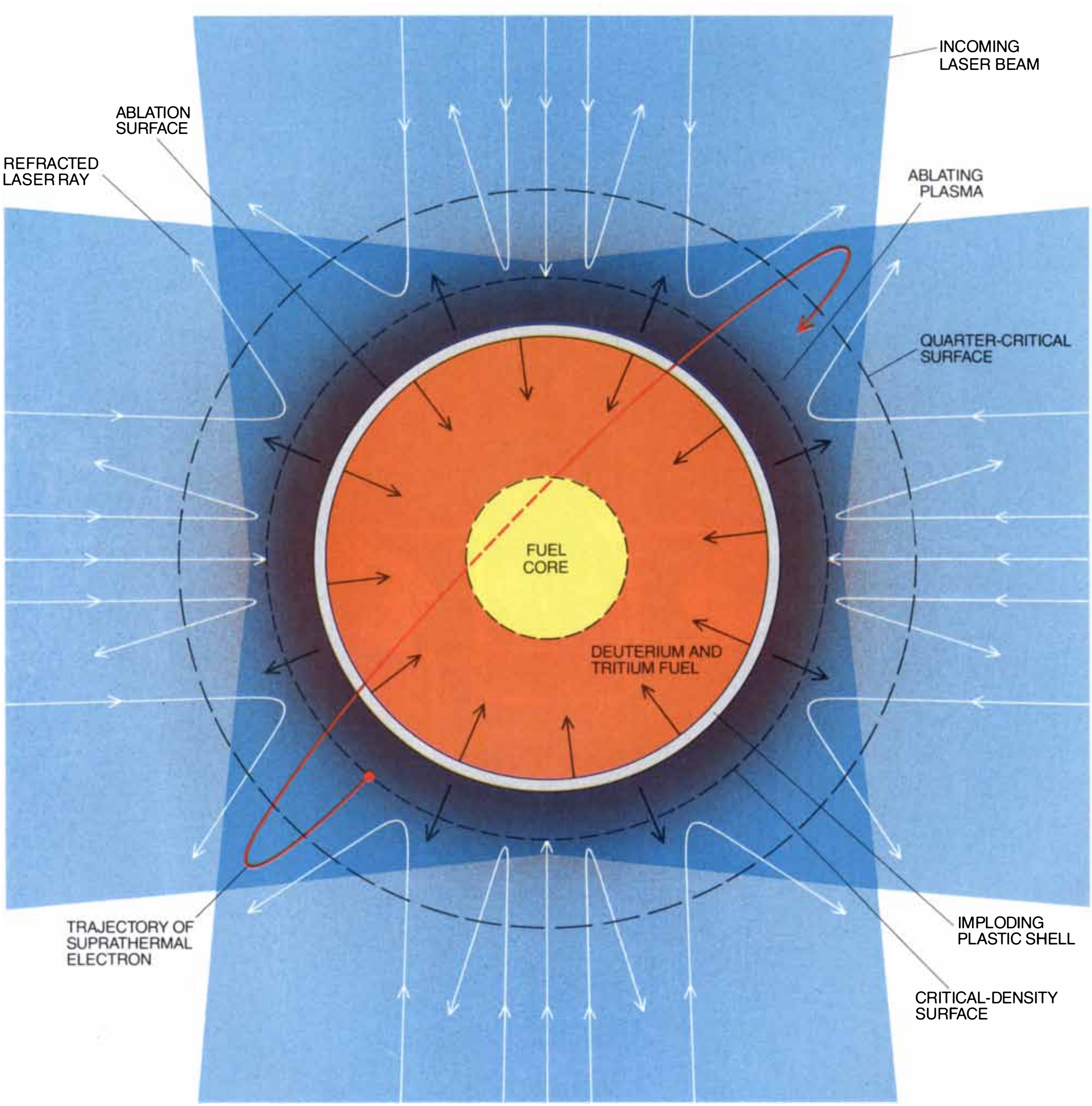
In a working fusion reactor the neutrons to which the reaction gives rise would escape from the fuel at high velocities and deposit their energy in the surrounding reactor chamber. In one design a layer within the wall of the reactor chamber would hold a fluid such



TARGET AREA of the OMEGA laser system, operated in the authors' laboratory at the University of Rochester, is shown in the photograph. The system is a neodymium-glass laser converted to a shorter wavelength in order to study the properties of fuel pellets for laser fusion. The laser first emits a single beam of infrared light at a wavelength of one micron. The beam is then amplified and split into 24 beams. After further amplification each of the 24 beams is passed through a cell holding two crystals of potassium dihydrogen phosphate (KDP), where it is converted into an ultraviolet beam at three times the input frequency. Mirrors and lenses guide and focus the beams into the target chamber, the complex spherical device at the center of the photograph. The target chamber is evacuated, and the fuel pellet is suspended at its center; the 24 focused laser beams converge on the pellet and deposit their energy there. Instruments for monitoring the effects of the laser energy on the pellet can be seen protruding from the upper hemisphere of the target chamber.

as lithium, which is known as a moderator. The neutrons would collide with the fluid and slow down, giving up their kinetic energy to the fluid in the form of heat. The fluid would circulate to a heat exchanger, which would then transfer the heat to pressurized, circulating steam, and electric power would be generated by steam-driven turbines in the usual way. The entire process is known as laser fusion.

Although we shall limit our discussion to laser fusion, we should note that particle-beam accelerators can also drive the compression of a fuel pellet. At the Sandia National Laboratories in Albuquerque construction has recently been completed on an accelerator called PBFA II (Particle Beam Fusion Accelerator), which will energize fuel pellets with beams of high-en-



LASER FUSION takes place in a fuel pellet, typically a small plastic shell about a millimeter in diameter that holds a mixture of deuterium and tritium fuel. The shell is irradiated uniformly from many directions by overlapping laser beams, and its outer portion is vaporized to form a plasma. The laser beams penetrate the plasma only up to the critical-density surface and deposit much of their energy in its vicinity. One mechanism for the energy absorption, called collisional absorption, is particularly effective at short laser wavelengths. Electrons oscillating in the electric field of the laser heat the plasma through collisions with one another and with ions in the plasma. The thermal energy of the heated plasma is then conducted inward to the ablation surface, the boundary between the hot plasma and the dense shell. The plasma outside the ablation surface explodes away from the rest of the shell like the exhaust plume of a rocket. The reaction force causes the shell to be driven inward toward the center of the fuel pellet. The implosion compresses the fuel into a dense core and heats it; thermonuclear reactions can then take place. For long-wavelength lasers a substantial fraction of the laser energy is deposited into unwanted, highly energetic suprathermal electrons. Such electrons can penetrate the core and heat the fuel in the initial stages of the implosion, thereby precluding the high compression needed in the core to achieve fusion ignition.

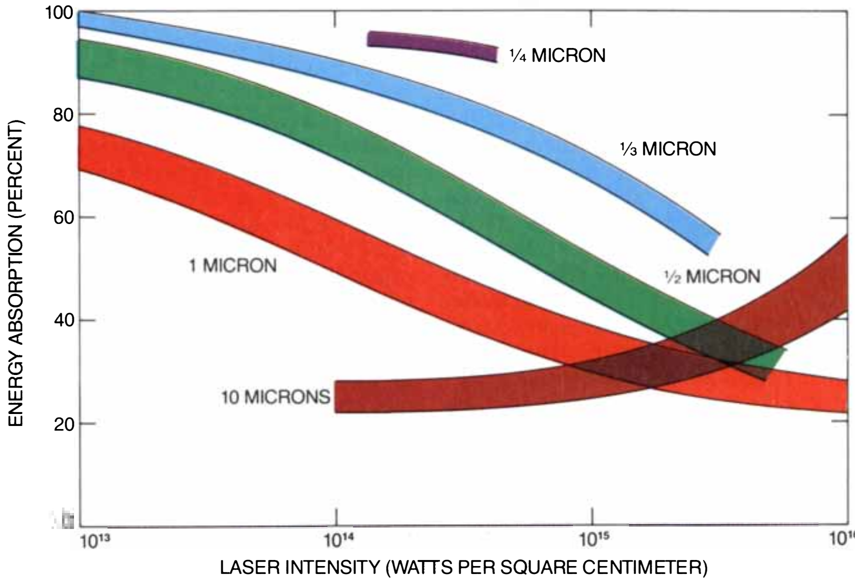
ergy lithium ions. The general term for all such schemes of generating fusion in a pellet by compressing it, whether by laser, particle beam or some other energy source, is "inertial-confinement fusion."

Frequency-converted Lasers

Until quite recently lasers powerful enough to drive fusion reactions had been built only for emission wavelengths in the infrared. Most of the experimental work to develop laser fusion has been conducted with two kinds of infrared laser: the solid-state, neodymium-doped glass laser, whose wavelength is one micron, and the carbon dioxide gas laser, whose wavelength is 10 microns. By the end of the 1970's, however, extensive experiments and elaborate computer simulations had identified a fundamental difficulty. For lasers emitting at the intensities needed for fusion and at wavelengths of one micron or longer, less than half of the laser energy is absorbed by the fuel pellet. Furthermore, of the energy that is absorbed a substantial fraction gets carried away by so-called suprathermal electrons. Such electrons pass freely through the fuel pellet and heat the fuel before it can be compressed. The premature heating precludes achieving the high densities needed for fusion.

Investigators quickly realized that the unwanted preheating of the fuel might be avoided if high-power lasers having wavelengths shorter than the infrared could be built. The apparent impasse posed by the unavailability of such lasers was sidestepped by an interesting optical trick. By carefully growing perfect crystals and then cutting each one at a precisely calculated angle with respect to the orientation of its crystal lattice, devices can be made that generate the higher harmonics of the incident beam. The frequency of the harmonics is two, three or a higher integer times the frequency of the input wave, depending on the number of crystals employed and their orientation within each device; the wavelength of the corresponding higher-harmonic beams is shortened by the same integral factor.

For example, if long-wavelength infrared laser light is passed through one crystal, a large fraction of the light energy can emerge as shorter-wavelength green light at twice the frequency of the input. If the green light and the residual infrared light from the first crystal are passed through a second crystal, they can be combined into a beam of even shorter-wavelength ultraviolet light with three times the frequency (a third of the wavelength) of the original infrared beam.



ABSORPTION EXPERIMENTS at different laser wavelengths show that the energy absorbed by a fuel pellet increases significantly as the wavelength of the laser decreases to less than one micron. The effect is particularly strong in the intensity range of 10^{14} to 10^{15} watts per square centimeter, which is the range required for generating fusion in a reactor with laser irradiation. For such wavelengths the high absorption at low intensity and the decline in absorption at higher intensities are characteristic of collisional absorption, which leads to the desired heating of the plasma surrounding the pellet. The fraction of the incident energy absorbed by unwanted suprathermal electrons increases with laser wavelength.

In one experiment at the École Polytechnique in France a one-micron beam from a neodymium-glass laser was passed through two crystals of potassium dihydrogen phosphate (KDP) in succession; the wavelength of the beam was reduced by a factor of two in each crystal, and the total reduction was therefore a factor of four. A target pellet absorbed almost all the energy of the frequency-converted beam, and suprathermal electrons were not detected. In such early experiments only a small part of the incident light was converted into light of higher frequency, but the results were still very encouraging. Investigators began directing greater attention to the physics of harmonic-frequency conversion and to methods for improving the conversion efficiency of existing neodymium-glass lasers.

Temperature and Density

To appreciate the need for the extraordinary scientific efforts being devoted to frequency conversion and other aspects of laser-fusion technology one must understand the physical environment required if laser fusion is to generate economically useful energy. The temperature of the fuel in each pellet must reach almost 100 million degrees Celsius, several times the temperature at the center of the sun. Simultaneously the fuel must be compressed to a density typical of what is found in the center of the sun: more than 1,000 times its ordinary solid or liquid density of .2 gram per cubic centimeter. The pressures corresponding to such a temperature and density are immense; indeed, pressures on the order of several billion atmospheres have already been generated in laser-driven implosions. Furthermore, macroscopic quantities of fuel must be brought to such conditions. The creation of such an environment not only would have immediate application to fusion power but also would open the possibility of doing experiments of direct relevance to astrophysics in the terrestrial laboratory.

The need to heat fusion fuels derives from the basic energetics of nuclear interactions. At a very short range the protons and neutrons that make up atomic nuclei are attracted to one another by the strong nuclear force. Many systems of nuclei can therefore increase their binding energy if the nuclei fuse. The total mass of the reaction products is slightly less than the sum of the masses of the fusing nuclei. Thus, in accord with Einstein's equivalence between energy and mass, the mass lost in the reaction is converted into energy, which shows up as the kinetic energy of the reaction products.

There is an important energy barrier

to this path for reducing potential energy. At temperatures less than about 10 million degrees C. the mutual electrostatic repulsion of the positively charged protons in the nuclei keeps the nuclei from coming close enough to "feel" the attraction of the strong force. Only within a distance of about 2×10^{-13} centimeter—comparable to the radius of the nucleus itself—does the strong force become dominant. To approach within this range two nuclei must be brought together with considerable kinetic energy; in other words, their temperature must be raised substantially. An important reason for the selection of deuterium and tritium ions as fusion fuels is that each ion carries only one positive charge, and that small charge minimizes the mutual repulsion of the fuels.

High compression is not a theoretical prerequisite for fusion, but it enhances the efficiency of the fusion reactions, and it is essential in a practical reactor design. The laser input energy needed to fuse deuterium and tritium efficiently at ordinary densities is well beyond the capacity of present laser technology. When the fuel in the pellet reaches its peak compression, the kinetic energy of the imploding material is converted into heat, and the confinement of that heat to the small compressed region raises the temperature of the fuel. Thermonuclear burning begins in a small "spark plug" region at the center of the fuel. Four-fifths of the energy released by the burning emerges as the kinetic energy of neutrons, which pass through the surrounding plasma and deposit their energy into a fluid circulating in the reactor chamber or into a moderator in the reactor wall.

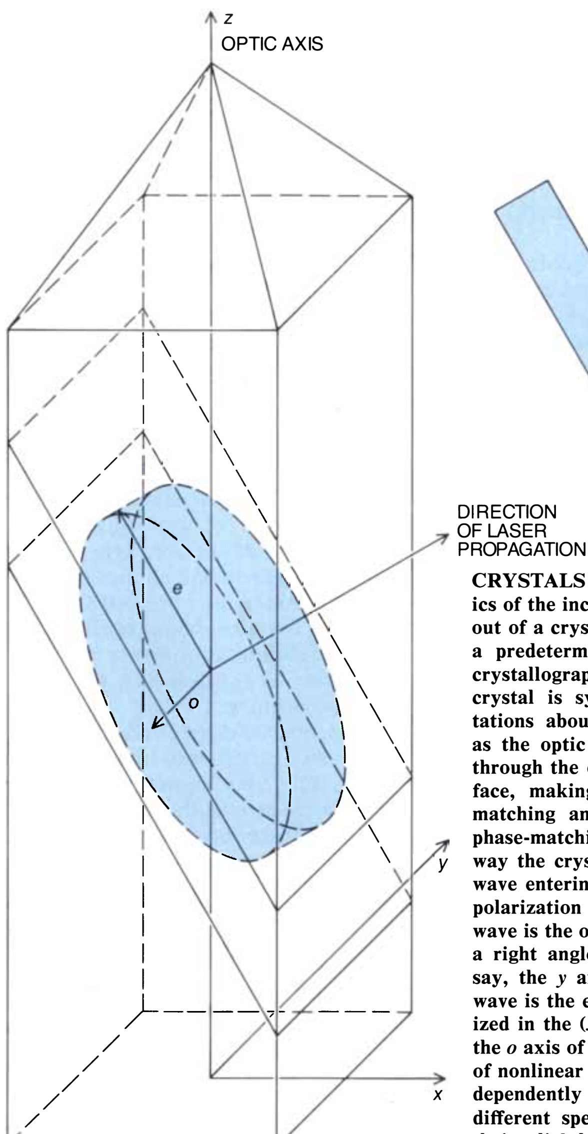
The other 20 percent of the energy released by the fusion reactions is carried away by alpha particles. Because they are charged particles, they are slowed by the fuel much more effectively than the neutrons are. They collide with the surrounding fuel and give up their kinetic energy over a distance inversely proportional to the fuel density. A sizable fraction of the fusion energy can thus be deposited in the cooler layers of the compressed fuel if the fuel is dense enough and its radius is large enough to stop the alpha particles. Such partial absorption of the fusion energy in the fuel is critical to the efficient propagation of thermonuclear burning; it is called bootstrap heating. When the energy deposited in the fuel by the alpha particles exceeds the energy needed to compress the fuel, the pellet is said to have ignited. If the attainable value of the compressed fuel density is known, the core radius, the fuel mass and the laser energy needed for ignition can all be determined. Achieving ignition would be a milestone in demonstrating the scientific feasibility of laser fusion.

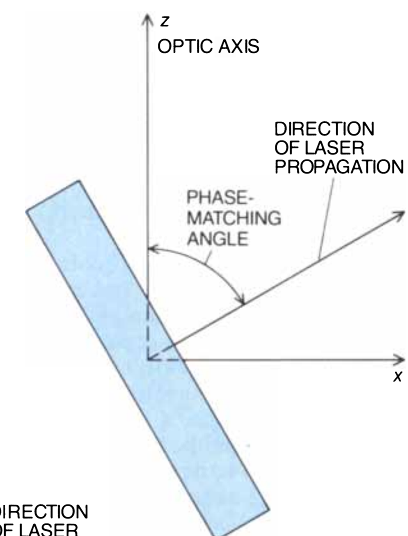
There is a small price to be paid for high compression: soon after fusion begins it must cease because the high internal pressure of the compressed fuel causes it to fly apart. The higher the compression is, the faster the fuel disassembles. Nevertheless, the high reaction rate at high compression more than compensates for the limited burning time. For example, other things being held constant, a tenfold compression of the radius of the fuel increases the reaction rate by a factor of 1,000, whereas the duration of the burning is reduced by a factor of only 10. It should be noted that in magnetic fusion devices the density of the fuel is 10 billion times lower than it is in the burning core of the pellet. The design must compensate for the low density by confining the fuel for 10 billion times as long.

Collisional Energy Absorption

Given the need for high temperature and high density of the fuel, which of the many physical processes relevant to laser fusion are the most important to understand and control? It turns out that the most critical processes depend on details of the interaction of the laser light with the plasma corona, or atmosphere, surrounding the fuel pellet. For example, the transfer of energy from the laser to the ablation layer begins in the corona. Furthermore, the degree to which the fuel is preheated by suprathermal electrons, prior to the implosion, is intimately related to the plasma physics of the corona.

After the first incident laser irradiation ionizes the outer surface of the



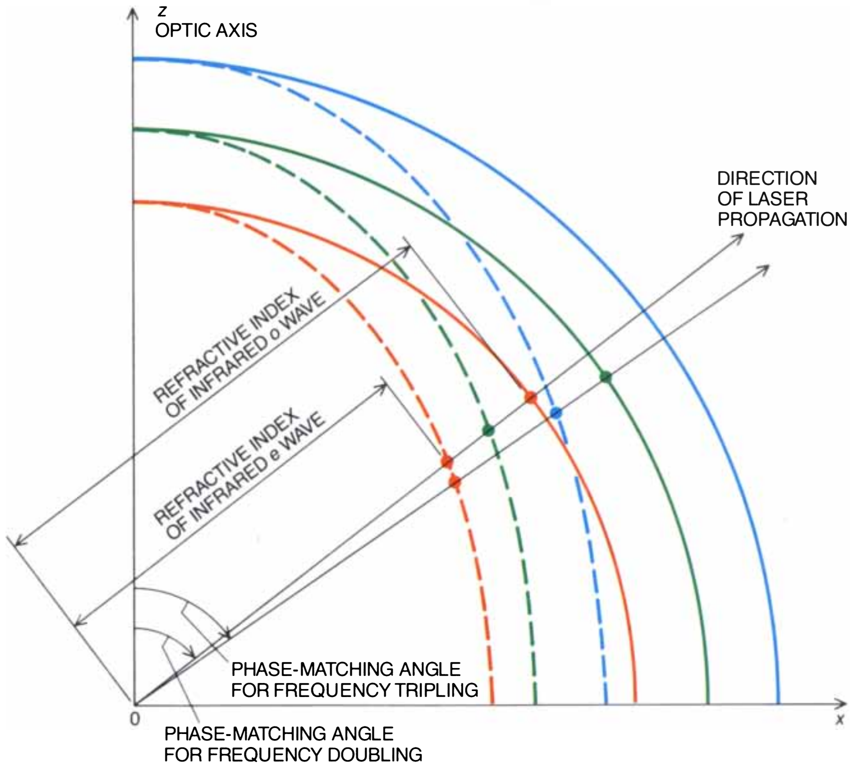


CRYSTALS for generating higher harmonics of the incident laser frequency are sliced out of a crystal block as circular disks with a predetermined orientation to the three crystallographic axes *x*, *y* and *z* (*left*). The crystal is symmetric under 90-degree rotations about the *z* axis, which is known as the optic axis. The laser is propagated through the disk at a right angle to its surface, making an angle called the phase-matching angle with the optic axis. The phase-matching angle is determined by the way the crystal disk is cut (*above*). A light wave entering the crystal with an arbitrary polarization splits into two waves. The first wave is the ordinary, or *o*, wave polarized at a right angle to the optic axis and along, say, the *y* axis of the crystal. The second wave is the extraordinary, or *e*, wave polarized in the (*x*-*z*) plane and perpendicular to the *o* axis of the crystal disk. In the absence of nonlinear effects the two waves travel independently through the crystal at slightly different speeds, which are determined by their slightly different refractive indexes.

pellet, the resulting plasma corona begins to expand outward. The corona is dense near the surface of the pellet and becomes rarefied at larger radii. The rapidly oscillating electric field of the subsequent incoming laser light causes rapid oscillations of the lightest charged particles in the plasma, namely the electrons. A current is therefore set up in the plasma, oscillating at the frequency of the driving electric field and proportional to the density of the electrons in the plasma.

In the rarefied outer regions of the corona the current is small, but in the inner regions, where the electron density is greater, the current becomes larger. At what is called the critical radius the current becomes large enough to shield the plasma at smaller radii from further penetration of the incoming electric field. The oscillating electric current acts as an antenna that broadcasts a second, outgoing electromagnetic wave, equal in frequency to the incoming wave but carrying energy away from the target. The electron density at the depth of maximum penetration of the incoming wave is called the critical density, and it is inversely proportional to the square of the laser wavelength. For example, a threefold reduction of the laser wavelength would give rise to a ninefold increase in the critical density.

Much of the absorption of the laser energy takes place in the vicinity of the critical-density surface. The oscillating electrons collide with ions in the plasma as well as with one another, thereby transferring part of their energy to the plasma as the energy of random motion, or heat. This mechanism for energy transfer is more efficient for a short-wavelength laser than it is for a long-wavelength laser, since the short-wavelength beam can penetrate to higher electron densities where collisions are more frequent. The heat energy is conducted inward to the ablation surface, the boundary between the exploding and imploding regions of the pellet. Collisional absorption accounts for virtually all the absorbed energy that contributes to the implosive compression of the pellet.



ORIENTATION OF DISK SLICE with respect to the crystallographic axes is determined by a simple geometric construction. The red arcs represent the input frequency of the infrared laser, and the green and blue arcs respectively represent the second and third harmonic frequencies. The refractive indexes of the *o* waves vary with wavelength but not with a change in the orientation of the slice with respect to the *z* axis. Hence the refractive index of the infrared *o* wave is shown as a red circular arc, and the indexes of the green and ultraviolet *o* waves are shown as green and blue circular arcs. The refractive indexes of the infrared, green and ultraviolet *e* waves do vary with the angle the slice makes with the *z* axis; the variations are plotted as red, green and blue broken elliptical arcs. The propagation direction for frequency doubling must be chosen in such a way that the refractive index of the green *e* wave is equal to the average of the refractive indexes of the infrared *o* and *e* waves. For frequency tripling the refractive index of the ultraviolet *e* wave must equal one-third of the index of the infrared *e* wave plus two-thirds of the index of the green *o* wave.

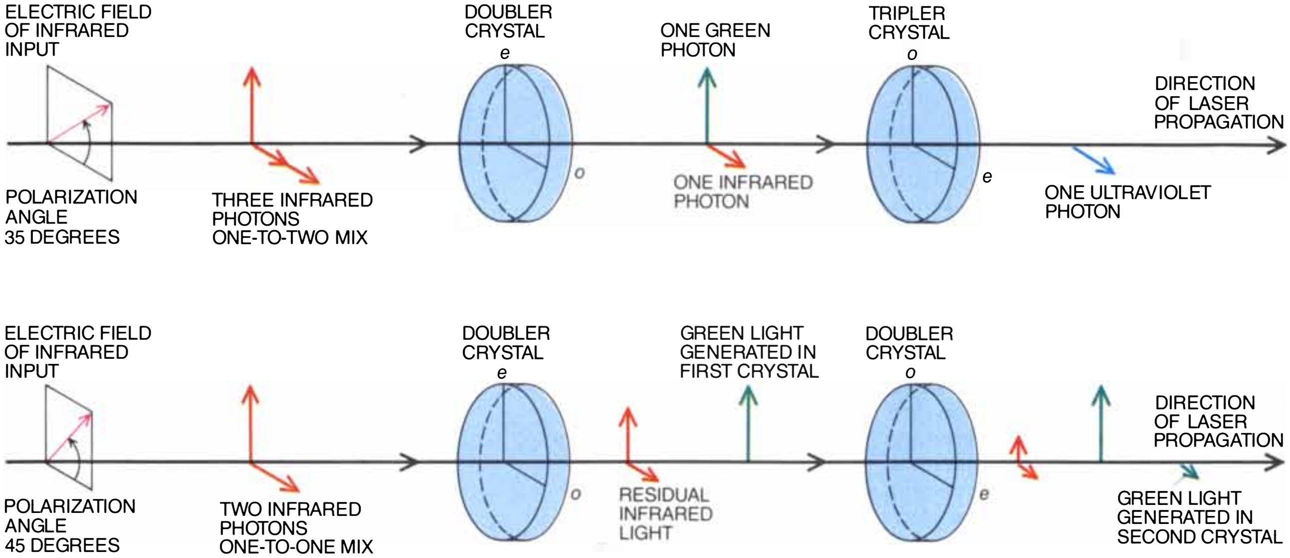
Suprathermal Electrons

There are several other mechanisms for laser-energy absorption that do not contribute to the heating or compression of the fuel but must be understood because they give rise to unwanted suprathermal electrons. As the name implies, the energy of a suprathermal electron is significantly higher than the average energy of the thermal electrons in the plasma. Such excess energy can be acquired only if the electron is accelerated by a large electric field for a sufficient time. The electric field of the laser, although intense, changes direction so often that the velocity of the electrons oscillating in the field is relatively small. Hence in most experimental conditions the electric field of the laser does not lead directly to suprathermal electrons.

Large electric fields can nonetheless arise in waves known as plasmons, which travel through the plasma. Plasmons are somewhat like sound waves in that they propagate as compressions and rarefactions of particles in the direction of the wave motion. Unlike sound waves, however, plasmons do not affect all the particles in the medium: the ions in the plasma are stationary and only the electrons move. Regions of net positive charge are thereby created in the rarefied electronic regions, and regions of net negative charge are created in the compressed regions. A large electric field is formed between a rarefied region and a compressed region, and there is a strong attractive force between the two.

Electrons that happen to be moving in the same direction as the plasmon and at roughly the same speed become trapped in the plasmon somewhat like a surfer riding a wave. Since they move with the same speed as the wave, they experience its electric field as a nonoscillating field. The field accelerates them to suprathermal velocities, which enable them to escape the plasma layer before collisions can slow them down.

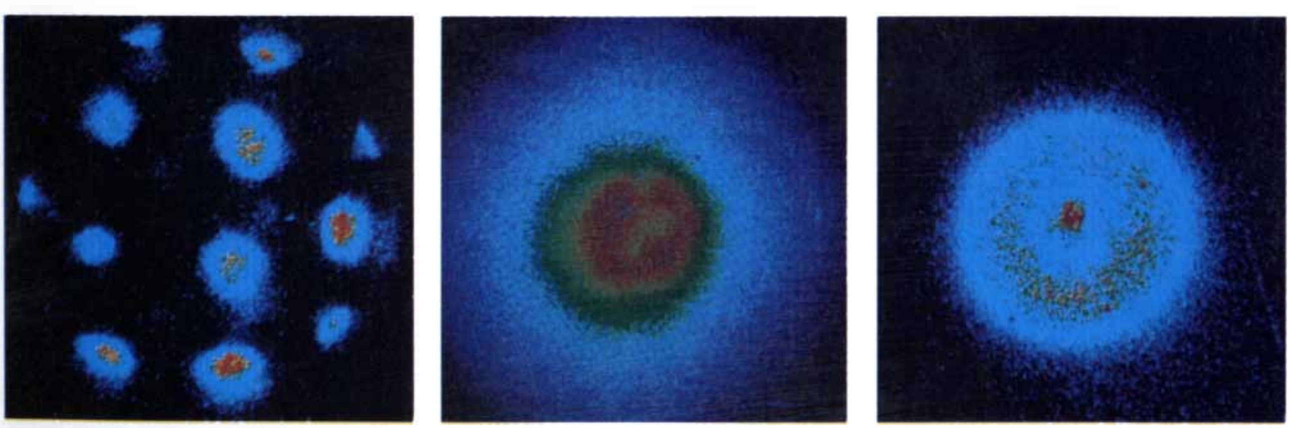
Plasmons can be generated in many ways. One important mechanism is called resonance absorption. As a laser ray penetrates the plasma, much of the energy of its oscillating electric field is given up to surrounding electrons. Near the critical-density surface, however, the natural oscillating frequency of plasmons equals the laser frequen-



ROCHESTER FREQUENCY-TRIPLING SCHEME (*top*) employs two crystals whose *o* and *e* axes are mutually perpendicular. The incident infrared laser beam is polarized at an angle of 35 degrees to the *o* axis of the first crystal. This ensures that two-thirds of the photons incident on the first crystal are aligned with its *o* axis and one-third are aligned with its *e* axis. One *o* photon combines with an *e* photon to give an *e* photon at the second harmonic (*green*), or at twice the frequency of the incident light. The green *e* photon combines in turn in the tripler crystal with the remaining infrared photon to give one ultraviolet photon at the third harmonic (*blue*). In the authors' laboratory the technique has been shown to be 80 percent efficient, and it is now employed in the NOVA laser at the Lawrence Livermore National Laboratory. A simple reorientation of the two crystals (*bottom*) also makes it possible to generate the second harmonic in the NOVA laser with improved efficiency. The input beam is polarized in such a way that the numbers of infrared *o* and *e* photons are equal. The doubling process is less than 100 percent efficient, and some residual infrared photons remain unconverted after passing through the first crystal. When the second crystal is tilted through a small angle from its position for frequency tripling, it becomes a doubling crystal, and residual infrared photons have a second opportunity to be converted to green.

cy. The energy that reaches this depth in the plasma can drive plasmons resonantly to large amplitudes, much as a child on a swing can go progressively higher by pumping in synchrony with the swing's natural motion. The energy that is pumped into resonantly driven plasmons is eventually released as the kinetic energy of suprathermal electrons.

There are two further important mechanisms whereby plasmons can form and generate suprathermal electrons. Although both mechanisms appear to be less significant causes of preheating than resonance absorption, it is worthwhile to explain them briefly. Both of them arise out of a phenomenon called three-wave mixing, which also plays a major role in harmonic-frequency conversion. In three-wave mixing two waves can interact through the matter in a plasma or a crystalline solid to produce a third wave. In general the mixing is strongest when the amplitudes of the interacting waves are large. The frequency of the third wave equals the sum of the frequencies of the two input waves. The direction of the process is also re-



X-RAY IMAGES can determine the uniformity of laser irradiation on a fuel pellet. The color-enhanced image at the left shows the X-ray emission when all 24 beams of the ultraviolet OMEGA laser are focused onto small areas of the pellet. Such illumination does not lead to symmetric compression, but it is useful for testing the pointing and focusing of the laser beams. The other images are from imploding pellets irradiated with overlapping beams. In the middle is a large pellet with a thin glass shell and at the right is a smaller pellet with a thick glass shell; both pellets are filled with deuterium and tritium gas. The red parts of each image are the regions of highest X-ray emission from the compressed part of the shell. The thick shell maintains the fuel at a lower temperature than the thin shell does, and it also generates a higher compression of the fuel. The X-ray emission extends just beyond the initial pellet surface.

versible: from a "product" wave two new "factor" waves can emerge.

The first mechanism for the formation of plasmons is known as the two-plasmon instability. Here the laser beam functions as the product wave, and it splits into two plasmons, which function as the two factor waves. The frequency of each plasmon is half the frequency of the incoming beam. Since the critical density of the plasma electrons varies inversely with the square of the input wavelength, the two plasmons are driven resonantly when the electron density in the plasma is a quarter of the critical density for the input laser. Hence the two-plasmon instability arises near the so-called quarter-critical surface [*see illustration on page 70*].

The second mechanism for plasmon formation is called Raman scattering; again the laser beam is the product wave, and its factor waves are a plasmon and a reflected light wave. Raman scattering can take place at the quarter-critical surface and in more rarefied regions of the plasma. The plasmons created by the two-plasmon instability and by Raman scattering generate suprathermal electrons in much the same way as they do in resonance absorption.

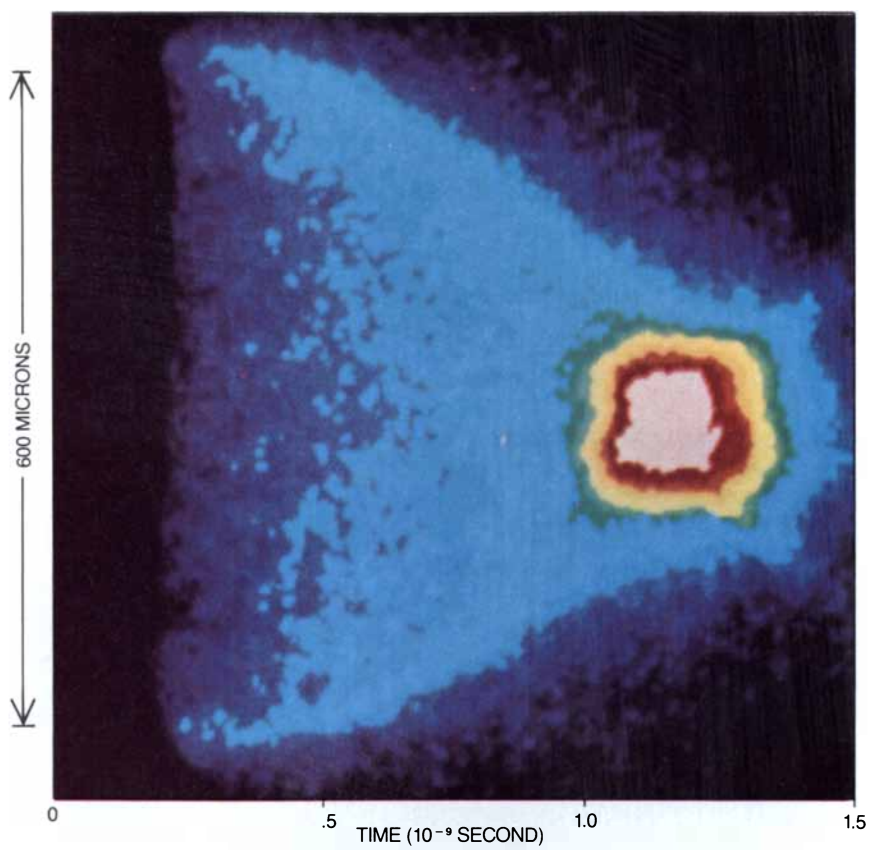
When the first suprathermal electrons escape from the corona, they leave a net positive charge on the pellet. The charge attracts later, outward-moving suprathermal electrons back toward the pellet, whereupon they overshoot their original positions and pass on into the pellet core. Some of the most energetic electrons may oscillate several times through the pellet before collisions with the fuel finally slow them; the transfer of collisional energy to the fuel preheats the fuel. The attractive electrostatic force between the suprathermal electrons and the ions in the corona can also lead to the outward acceleration of highly energetic ions. The loss of energetic ions from the ablation layer also drains away laser energy that might otherwise drive the implosion.

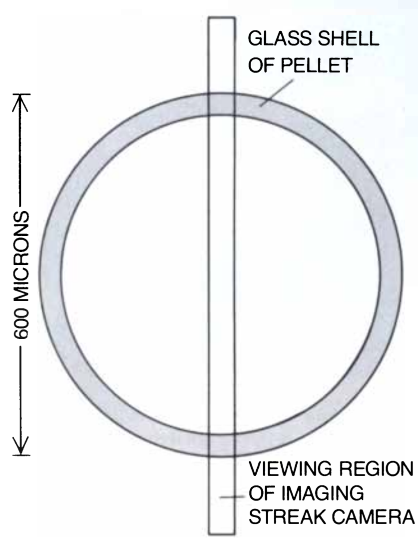
Experiments show that for the range of beam intensities relevant to laser fusion—generally from 10^{14} to 10^{15} watts per square centimeter—collisions are weak at infrared wavelengths and resonance absorption is dominant. For wavelengths shorter than .5 micron, however, a variety of experimental results suggest that collisional absorption is the most important absorption mechanism. Moreover, at such wavelengths neither the two-plasmon instability nor Raman scattering have been found to preheat the fuel significantly, although further experimental tests of these effects are needed for the larger pellets required in a commercial laser-fusion reactor. Thus empirical study to date has confirmed the significant advantages of short-wavelength lasers for fusion.

Frequency-Conversion Crystals

The desire to investigate how laser energy at submicron wavelengths can be exploited to compress fuel pellets has led to the recent interest in frequency-converted lasers. Since frequency conversion can readily shorten the wavelength of a laser to a half or a third of its ordinary emission value, the wavelength range of interest is experimentally accessible with existing neodymium-glass lasers.

Optical frequency conversion may become less critical as new kinds of lasers appear. For example, the krypton-fluoride laser, a gas laser under development at the Los Alamos National Laboratory and elsewhere, can also





IMPLOSION HISTORY of a spherical, glass fuel pellet uniformly illuminated by the OMEGA laser is captured in this color-enhanced photograph. An X-ray pinhole camera forms an image of the pellet similar to the ones in the bottom illustration on the opposite page, and a mask with a slit is placed over the X-ray image (*left*). A streak camera then displaces the part of the image seen through the slit a distance to the right that is proportional to the time elapsed during the implosion. The resultant image (*upper image*) thus portrays the implosion in both space and time. Soon after the laser begins illuminating the pellet, X rays are emitted from the plasma near its initial surface. As the pellet is compressed the region emitting X rays moves closer to its center, until a bright flash of X rays is visible at peak compression, about one nanosecond after the implosion begins. The speed of the imploding shell is about 200 miles a second.

deliver the high energies needed for fusion implosion; its emission wavelength is only .25 micron. Yet although the krypton-fluoride laser is widely considered to be a promising candidate for a reactor laser, questions related to the efficiency with which it can deliver the short pulses of energy needed in a reactor are still under study. The neodymium-glass laser remains the major research tool for the study of short-wavelength, laser-fusion implosions.

Many kinds of crystal have been incorporated into small laser systems for converting laser light to its higher harmonic frequencies. The crystal KDP, however, is the only one that has so far been grown large enough for current work. KDP crystals are grown from solution at a rate of only a few centimeters per month. The largest available crystals of acceptable quality are more than 30 centimeters in diameter and take as long as a year to grow. Circular slices about one centimeter thick are cut from the crystal, polished and mounted in the path of a laser beam.

One crystal can generate the second harmonic, a wave at twice the frequency of the fundamental beam. A second crystal mounted in the path of the first output beam can then mix the generated second harmonic with the residual fundamental to produce the third harmonic [*see top illustration on page 74*], or the crystal can generate the fourth harmonic by a second doubling process. In principle there is no upper limit to the frequency that could be generated by successive stages of doubling, but unfortunately suitable crystals transparent to wavelengths shorter than .2 micron are not available.

Harmonic Generation

The capacity of some crystals to generate higher harmonic frequencies of a laser beam was discovered soon after the invention of the laser. Investigators at the University of Michigan found that a laser beam focused into a crystal of quartz emerged from the crystal with some light at the second-harmonic frequency. As we mentioned above, the phenomenon is an example of three-wave mixing; in this case two components of the input laser beam make up the two factor waves, and the higher-harmonic output is the product wave. The two components of the input beam arise as the beam enters the crystal because of asymmetries in the alignment of the atoms that make up the crystal lattice.

When the oscillating electric field of the laser enters the crystal, it displaces electrons from their equilibrium locations, just as it does in the corona of the fuel pellet. In a KDP crystal the electrons are harder to displace along a preferred axis called the optic axis, or *z* axis, than they are along any direction lying in the *x*-*y* plane perpendicular to the *z* axis. The crystal is "stiffer" to the force of the electric field along the optic axis, and the electromagnetic wave whose electric field is aligned with the optic axis propagates the fastest through the crystal.

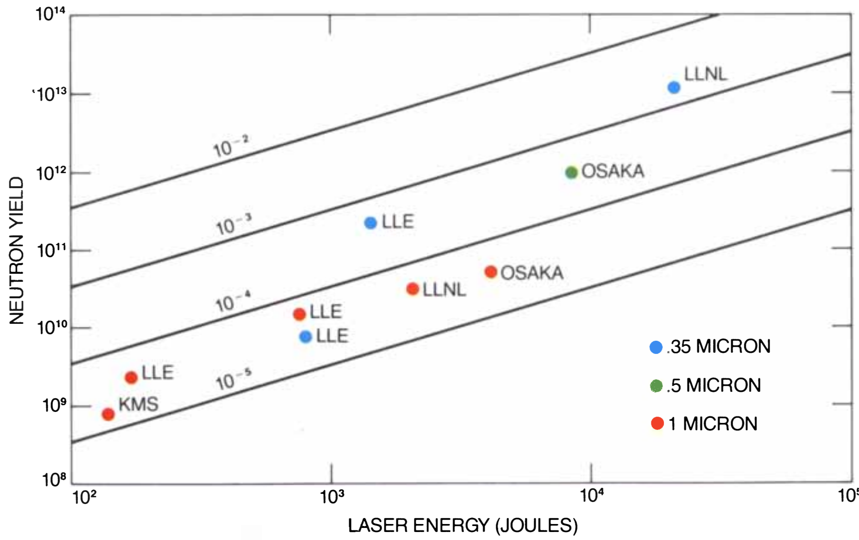
Imagine that the crystal is cut so that its face makes an oblique angle to the *z* axis, and suppose a light ray strikes the crystal at a right angle to its face [*see illustration on page 72*]. The electric field of the ray, which then oscillates parallel to the face of the crystal, has two mutually perpendicular components. The first component, which lies

BEAM SPLITTING, amplification and frequency tripling of the OMEGA laser are carried out in the large room shown. The bright areas on the far wall (160 feet from the camera) are caused by flash lamps that energize the laser amplifiers. The laser beams are infrared, and so they are invisible. They are converted into invisible ultraviolet light by crystals in the six boxlike modules. The visible light emerging from some of the modules comes from heat lamps, switched on intermittently to keep the crystals at a constant temperature. Residual green light from the conversion causes the green glow. The beams emerge from the modules in groups of four, and their energy is measured. Subsequently the beams are reflected by the mirrors visible in the foreground into the adjacent target area.

in the x-y plane and is parallel to one of the crystal axes (by convention the y axis), is called the ordinary, or *o,* ray. Because it has no component in the z direction, it propagates relatively slowly through the crystal. The second component of the incident ray is perpendicular to the first one in the plane of the crystal face. This second component is called the extraordinary, or *e,* ray, and it does have a component in the z direction. Because of its z component, which depends on the orientation of the crystal face with respect to the z axis, the *e* component of the incident beam moves through the crystal faster than the *o* component.

When high-intensity laser light travels through a crystal, the electrons displaced by the electric wave tend to feel a restoring force that is neither in the same direction as their displacement nor proportional to it. It is the nonlinear, or nonproportional, response of the electrons to the *e* and *o* components of the electric field that gives rise to a so-called nonlinear current wave. The current wave is made up of electrons oscillating in the x-z plane at twice the frequency of the input laser beam, and it moves through the crystal at a velocity equal to the average velocity of the *e* and *o* components of the input laser. More precisely, the refractive index of the current wave is the average of the refractive indexes of the *e* and *o* components.

The current wave of oscillating electrons generates a wave of laser light at the second harmonic of the laser beam, just as oscillating electrons in an antenna generate radio waves. The second-harmonic light wave can be generated efficiently, however, only if it propagates at the same velocity as the current wave: it must "surf," or be in phase with, the current wave. Because the second-harmonic wave is an *e* wave, its velocity and therefore its refractive index vary with the angle between its direction of propagation and the optic axis. Hence the velocity of the second harmonic can be matched with the velocity of the current wave by cutting the crystal in such a way that the direction of propagation of the laser through the crystal makes a predetermined angle with the optic axis [*see illustration on page 73*].



NEUTRON YIELD obtained with several laser systems depends primarily on laser wavelength, energy and the symmetry of the incident beams. The sloping lines on the graph indicate the energy gain of the pellet: the fusion energy generated divided by the input laser energy. Results are from KMS Fusion, Inc., of Ann Arbor, Mich. (KMS); Lawrence Livermore National Laboratory (LLNL); the Laboratory for Laser Energetics at the University of Rochester (LLE), and the Institute for Laser Engineering in Osaka, Japan (OSAKA).

Attaining High Compression

Two more features of laser-fusion design, complementary to the requirement for a short-wavelength input beam, are crucial for reaching high fuel compressions in the pellet. They are the uniformity of the illumination and absorption of the incident laser beams and the hydrodynamic stability of the imploding pellet.

The uniformity of the illumination and absorption is important for purely geometric reasons. If the radius of the compressed shell is to be decreased by a factor of 30, the implosion velocity must be uniform over the surface of the shell to within about one part in 60. That requirement limits the allowable fluctuations of the laser irradiation intensity to one or two parts in 100 over the surface of the pellet.

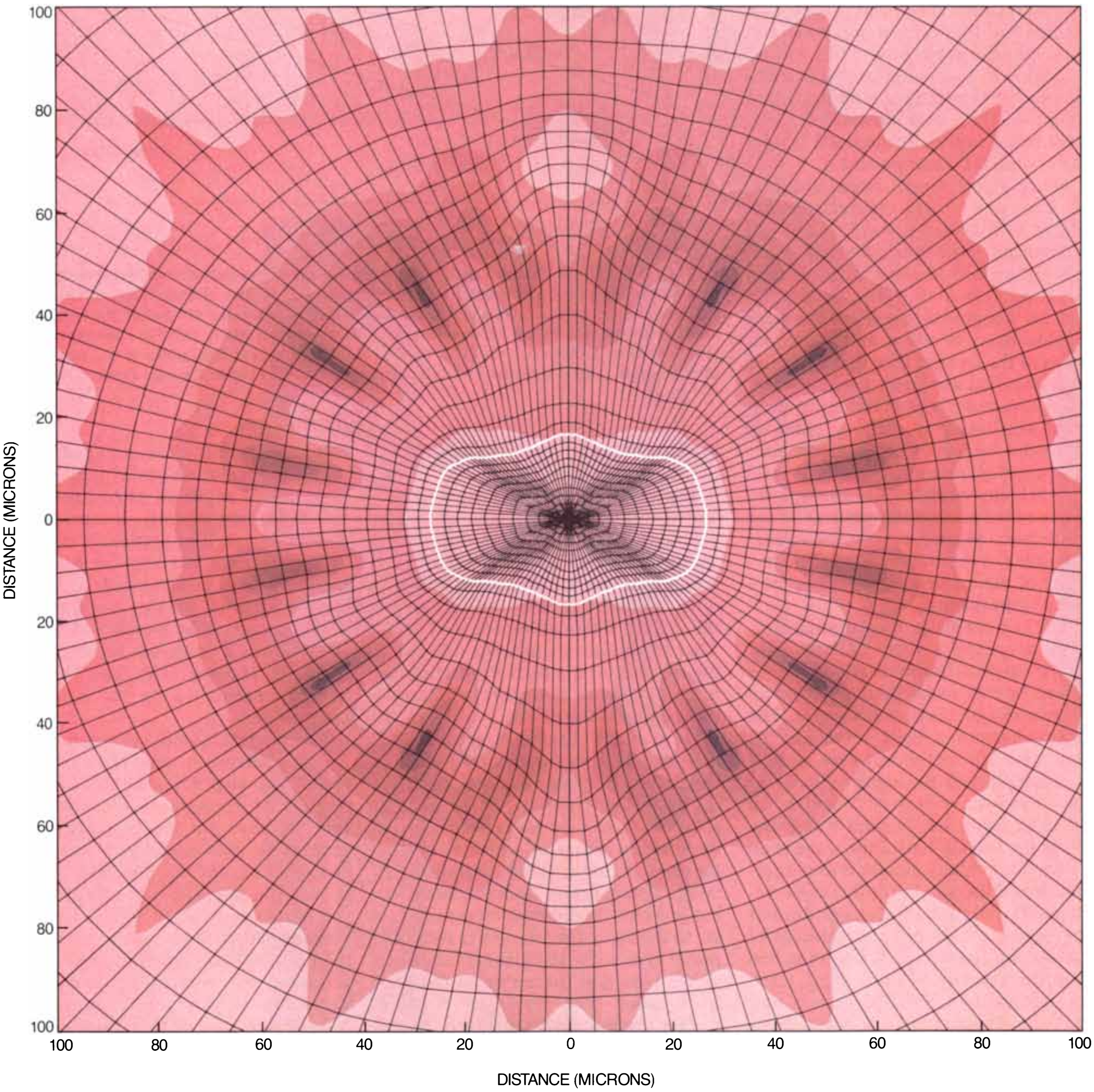
How many beams are needed, and how should they be arranged around the pellet? For laser systems employing four, six, eight, 12 or 20 beams, each beam can be positioned as if it were at the center of a face of one of the five Platonic solids (tetrahedron, cube, octahedron, dodecahedron or icosahedron) and directed perpendicular to the face. The beams are then disposed symmetrically around the pellet if it is placed at the center of the Platonic solid. The frequency-doubled VULCAN laser at the Rutherford Appleton Laboratory in England, and the GEKKO-XII laser in Osaka both employ a dodecahedral geometry. When the number of beams is greater than 20, or in other words greater than the number of faces in the regular icosahedron, suitable geometric configurations that maximize the uniformity of the illumination can be calculated. For example, a 32-beam system can be based on the configuration of the 32 pentagonal and hexagonal faces of a soccer ball.

Symmetric placement of the surrounding beams does not guarantee uniform irradiation of the pellet, however: not all points on a hemisphere of the pellet are equally irradiated by a given beam. The attainable irradiation uniformity increases as the number of beams is increased, although the complexity of the laser system also increases. The number of beams is therefore a trade-off between uniformity and complexity. The 32-beam system appears to be an attractive compromise.

The optical quality of each beam and the balance of energy among the beams are also important to the uniformity of irradiation. In our laboratory we have put much emphasis on generating laser beams with a uniform cross section, and we have been able to reduce the intensity variations across the profile of a beam to less than 10 percent. Other methods of enhancing the illumination uniformity have been proposed by workers in Osaka and at the Naval Research Laboratory in Washington. In both methods optical systems near the focusing lens fragment each beam that is split from the master beam into many—say 400—smaller beamlets. Each beamlet is given a random phase, and each spreads its energy over a full hemisphere of the pellet. Any spatial nonuniformities in any of the beams at the focusing lens are then averaged out over the pellet surface. Initial results from both laboratories show that the methods improve the uniformity of irradiation.

Another major goal in the study of

laser fusion is to understand and control hydrodynamic instabilities of the fuel pellet. When the imploding shell is decelerating just before the peak compression of the fuel, the dense fluid of the plasma shell can fall in spikes and mix with the deuterium and tritium fuel. At the same time the fuel can rise through the dense plasma in bubbles. The instability is similar to a phenomenon of incompressible fluids called the Rayleigh-Taylor instability, in which a dense fluid falls through a light one. It can be triggered by nonuniformities of irradiation or by imperfections in the shape or composition of the pellet, particularly when such imperfections are small. The ablation surface outside the fuel layer can also become hydrodynamically unstable as the implosion accelerates.



COMPUTER SIMULATION of the implosion of a fuel pellet designed for a reactor illustrates the effect of irradiation nonuniformities on pellet performance. The nonuniformities are assumed to be symmetric for rotations about the north-south axis of the pellet. They are characterized by the number of maximums of irradiation intensity encountered around the great circle represented by a line of longitude on the pellet. The pellet is a plastic shell with a layer of cold, liquid deuterium and tritium fuel on its inner surface and a small amount of deuterium and tritium gas inside. When the gas is compressed, it forms a so-called spark-plug region in which thermonuclear reactions are ignited. An irradiation nonuniformity of 1 percent is imposed in the simulation. The illustration shows the compressed core just before ignition; darker regions correspond to higher densities. The grid lines indicate the resolution with which the evolution of the pellet implosion was calculated. The boundary between the main fuel and the gas, which was the inner layer of the shell before the compression, is shown as a white contour line. Most of the material shown is compressed to a density of between 100 and 500 grams per cubic centimeter, or from 500 to 2,500 times its liquid density. The calculation was done with the program ORCHID, written by Charles P. Verdon of the University of Rochester; it required tens of hours on a CRAY X-MP, one of the world's fastest supercomputers. In spite of the nonuniform compression the fusion yield in the simulation was nearly 100 times the laser-energy input.

That instability can lead to a breakup of the shell, a mixing of the fuel and the shell and a smaller peak compression. Ultimately such effects eliminate or reduce the thermonuclear yield.

One-dimensional spherically symmetric simulations show that the highest compressions can be obtained for pellets whose shells are thin compared with their radii. Hydrodynamic instability, however, is potentially most dangerous for pellets with thin shells. A realistic pellet design must therefore represent a trade-off between the desirability of relatively thin shells and the constraints imposed by uniformity and stability considerations. It seems desirable to ensure that the shell never becomes thinner than a few percent of the radius of the pellet throughout the implosion.

Two designs currently assume major importance. The shell in our simulation is made out of plastic, and it contains an inner, cryogenic layer of liquefied deuterium and tritium. The shell interior is filled with low-density deuterium and tritium gas at the vapor pressure of the cryogenic liquid. The use of plastics made out of elements of low atomic number reduces the emission of radiation from the plasma corona, which could preheat the fuel. Since the cryogenic pellet is essentially empty, the shell is free to accelerate inward until the final moments when its kinetic energy is converted into heat.

An important alternate pellet design, which we can mention only briefly, exploits the response of materials of high atomic number to laser irradiation. The fuel pellet is placed inside a so-called radiation case made out of a material such as gold. When the interior of the gold case is irradiated by the laser, a large fraction of the incident energy is transformed into X rays. The X rays then irradiate the pellet and cause it to implode in a highly uniform way. Since the laser beams do not irradiate the pellet directly as they do in the first design, this alternate scheme is called indirect drive.

Computer Simulations

We shall conclude by describing computer simulations of a fuel pellet that might be considered for a commercial reactor, irradiated by a krypton-fluoride laser whose energy is 1.6 million joules and whose wavelength is a quarter of a micron. (A joule is the energy needed to lift one kilogram approximately 10 centimeters.) In our simulations the laser energy is deposited with an average power of 3×10^{14} watts in a pulse whose intensity increases steadily for five to 10 nanoseconds. The intensity of the pulse is kept low enough to avoid generating significant numbers of suprathermal electrons in the plasma corona.

One important measure of the response of the pellet to the laser is called the spark-plug convergence ratio, the ratio of the initial radius of the spark-plug material to its final radius. To maintain the stability of the pellet the ratio should not be too high; we aim for a ratio of about 50. In our models we then impose nonuniformities from point to point in the laser illumination of the pellet. As the interface between the shell and the fuel decelerates near the time of peak compression, pressure variations and the growth of hydrodynamic instabilities cause the density contours to follow a complex pattern around the core [*see illustration on opposite page*].

The alpha particles emitted by thermonuclear burning in the spark-plug region begin to deposit their energy in the main fuel layer. When the product of the density and the radius of the spark-plug region rises to values large enough to stop most of the alpha particles, thermonuclear ignition is achieved. The temperature in the spark-plug region reaches approximately 100 million degrees C.; the temperature of the main fuel layer is about 30 million degrees. The thermonuclear burn propagates radially outward into the main fuel layer, the temperature profile becomes smoother and the burn becomes nearly spherical as the main fuel is consumed. The pellet then disassembles and the thermonuclear fire goes out.

According to our simulations, which have considered a variety of irradiation nonuniformities, the thermonuclear energy output is typically 100 times the energy input of the laser. These results inspire renewed confidence in the feasibility of laser fusion. A power plant capable of generating almost a billion watts might be feasible if 10 such fuel pellets were ignited every second and if the overall efficiency of the laser were approximately 15 percent. On the basis of these calculations we expect that a laser emitting more than 1.6 million joules of energy but less than 10 million joules would be appropriate for a reactor.

In summary, considerable progress has been made in understanding the physics of laser fusion, and the need for short wavelengths is now firmly established. The results of the next decade of experimentation should resolve the basic scientific question for laser fusion: Can ignition be achieved? An affirmative answer would bring the promise of abundant fusion energy for the 21st century one important step closer to its practical realization.