Laser fusion

Will a series of nuclear explosions in miniature pellets of hydrogen, ignited to fusion by laser-light beams, become a long-term method for supplying the world's energy needs?

C. Martin Stickley

Laser-driven fusion is one approach to a long-term solution to the world's energy supply problems, based on a virtually inexhaustible fuel source, deuterium from water. It is also, along with magnetically confined fusion, one of the most difficult scientific tasks ever undertaken.

The unique capability of the laser to attain very high instantaneous power density in a very small spot size introduces the possibility of driving thermonuclear fuel to the conditions of very high temperature and density at which fusion occurs. (These conditions are attained in a nuclear weapon by use of the energy release from a fission reaction, which drives a fuel mass to fusion conditions.) The success of laser-driven fusion also requires the delivery of a substantial part of the laser's energy to the fuel mass before heating the fuel—which would reduce the compression attained—and before a shock wave causes the fuel mass to disperse.[1]

Because much of the theory and many of the techniques required for laser fusion were already available from nuclear-weapons development, which has fostered fusion research since the early 1950's, the principal effort in the laser-fusion program has been to develop high-power, single-pulse lasers and to understand the dynamics of the laser beam's interaction with matter.

Laser versus particle beam

Fusion neutrons were first produced from heated and compressed fuel pellets in the United States—at KMS Fusion Inc, Ann Arbor, Michigan—in 1974. By 1976 the Lawrence Livermore Laboratory was able to demonstrate conclusively the thermonuclear origin of neutrons from pellet implosions, and obtain over 10^9 neutrons from repeatable experiments. Complex computer programs can predict the results of these with considerable accuracy over a wide range of neutron yields. A fusion-power system, using high-gain targets of a kind that could now be designed with some confidence, would produce on the order of 10^{19} high-energy neutrons (14.1 MeV). This energy could be converted to a variety of uses, including electric-power and synthetic-fuel production, fission-fuel enrichment and process heat. These applications are in general common to the various fusion approaches. However, inertially confined fusion induced by lasers also provides a capability for studying the physics of nuclear weapons and simulating their effects on a laboratory scale.

Particle-beam sources can perform the task of the laser in inducing fusion conditions in a very small fuel mass. Indeed, particle beams of very high energy are already available and their technology is comparatively well understood. However they, like lasers, have characteristic problems associated with their use. Forming the beam and focussing it on a point at a distance from the beam source are the most critical of these.

Our understanding of these target-related issues is not as well advanced as our command of the source technology. Nevertheless, successful fuel-pellet implosions with electron beams were attained in the Soviet Union in 1975 and at Sandia Laboratories, Albuquerque, late in 1976. A parallel effort, mainly in the high-energy-physics community, to determine the adaptability of the technology of heavy-ion accelerators to fusion has been under way for little more than a year.

The inertial-confinement-fusion program is still in an early stage relative to the goal of a working fusion-power system. However, significant accomplishments have been made in developing unique high-peak-power sources. Furthermore, we have gained sufficient command of the physics of laser- and particle-beam interactions with targets to project with some confidence the requirements for an ultimate inertial-fusion power system. The demonstration of scientific feasibility—the initiation of fuel burn with energy produced from the pellet exceeding the absorbed beam energy—may be achieved with laser energy on the order of a third to a half of a megajoule. Such a laser—the Nova neodymium-glass laser to be built beginning in 1979 at Lawrence Livermore Laboratory—is expected to be in operation in 1984–85. Figure 1 shows the 20-beam Nova facility, a 200–300 kilojoule upgrade of Shiva, which was discussed in a "Search and Discovery" article in last month's issue of PHYSICS TODAY (page 17).

Laser and particle-beam sources capable of being scaled to high peak powers and to high repetition rates of operation are being developed in parallel with the succession of Livermore-developed neodymium–glass lasers. Both parametric and economic studies indicate that inertial-fusion power plants are technically feasible and that fusion power based on inertial confinement could offer an alternative power source early in the next century.

Fundamentals

The capability of scaling inertially confined fusion reactions to reactor conditions is dependent on an understanding of fusion-driver–matter interactions.

For this discussion let us consider the driver to be a laser, although other drivers are presently under investigation. The

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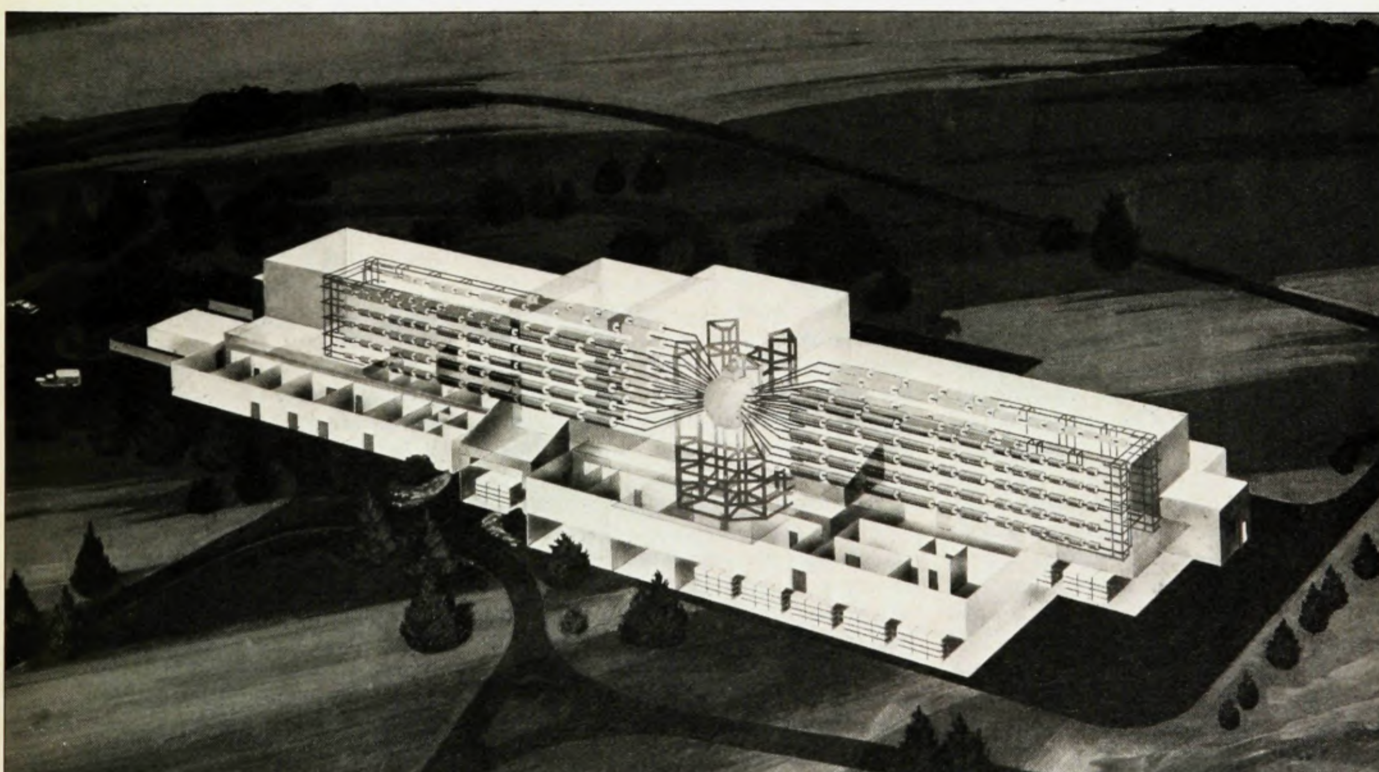
burning pellet consists of a dense inner core surrounded by a less dense plasma corona. The interaction physics leading to thermonuclear burn can be separated into four categories:

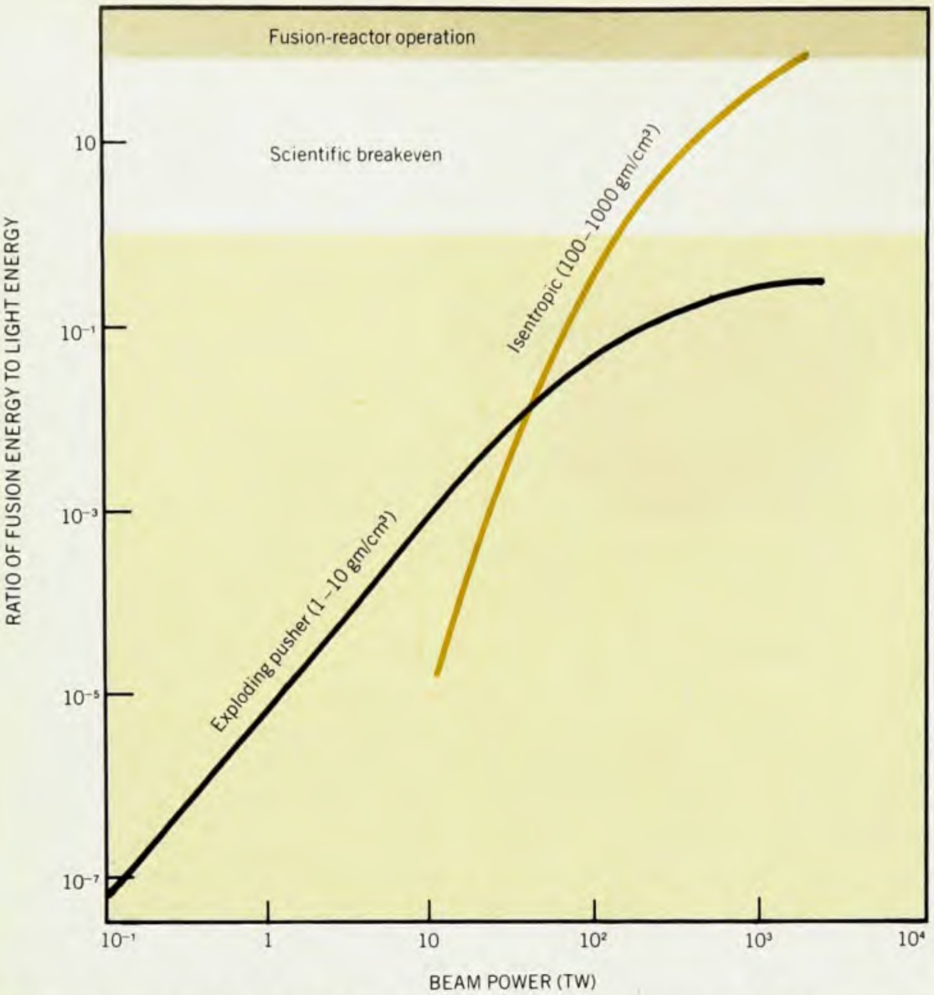
- absorption in the less dense region,
- transport of energy from the absorption region to the pellet core,
- hydrodynamics of compression, and
- fusion burn of the core.

Understanding of the absorption process has increased substantially in the last several years. The absorption is a combination of classical inverse bremsstrahlung and wave phenomena such as resonance absorption. Experimental measurements indicate that approximately one half the laser light incident on a plane is absorbed, as is one quarter of that incident on a sphere. The transport of the absorbed energy from the absorption region to the compression region is a nonclassical process in which electric and magnetic microfields inhibit the flow of energy. Studies of this effect indicate as much as a ten-fold inhibition can occur. Continuing study of these processes has led to the design of targets that optimize the energy flow into the compression region.

The energy transport is a combination thermal–shock wave, known as a "Marshak wave." This wave determines the physical character of the compressions. These occur when very weak (quasi-isentropic) shock waves are employed to compress the center while it is cool. If the center is heated first before compression begins, the initial core pressure would be



The Shiva Nova laboratory facility in a cutaway view. In 1984 the Nova 200–300-kilojoule neodymium-glass laser is to be completed, superseding the 10-kJ Shiva laser now operating at the Lawrence Livermore Laboratory in a twenty-beam configuration. Figure 1



Predicted energy gain from laser fusion in two types of pellets, isentropic and exploding-pusher targets. The gain for the exploding-pusher mode (illumination with very short pulses) has been verified experimentally for powers up to 4 terawatt on the target. The predicted gains for the two modes suggest that the high gains needed for breakeven and energy production can probably be attained only with the isentropic type of target. Figure 2

higher, and significantly more work would be required to compress the core. Once the target core is compressed and burning begins, the burn must last for a minimal time in order that a net energy gain is obtained. The energy generation in the fuel is related to the square of the fuel density and requires an ignition temperature of 5×10^7 K (5 keV) for reasonable fuel density. Thus the trend in inertially confined fusion is toward pellets capable of achieving high density. In addition, the burning fuel must be contained long enough so that a significant fraction is burned.

The desired confinement time is derived from the Lawson criterion, which says that the product of density and confinement time must be greater than 10^{14} sec/cm^3 for D–T burn above 5 keV. Thus densities and times on the order of 10^{25} ions/cm^3 and 10 picosec are required. The Lawson criterion simply states that a minimum set of conditions is required for breakeven. In fact, for power-plant application a significant target gain is required, greater than about 100; this may involve a higher Lawson number.

The compression and burn process can be optimized through a number of approaches. In the optimum burn sequence, in fact, the core remains relatively cold all through compression and only the very center is heated to ignition conditions; this then ignites the rest of the compressed fuel in a radially propagating burn. This is optimum because it takes much less energy to compress the core than to heat it; therefore heating only a small central core and letting a portion of the generated fusion energy heat the remainder of the fuel minimizes the laser or driver energy required for net energy generation.

A concept related to this central ignition is the development of pellets in which the product of compressed density ρ and radius r is greater than 0.3 gm/cm^2. When this product is greater than 0.3, a large percentage of the high-energy protons and alpha particles produced do not escape from the fuel region but deposit their energy into the fuel instead. Thus the fuel remains hotter and burns more effectively.

For targets with both dense compressions of high ρr and central ignition, energy gains of 1000 have been projected. These high-gain targets are more complex than the single-glass-shell microballoons containing deuterium–tritium gas currently used. These simple shells are typically 100 microns in diameter and a few microns thick with a gas fill of a few to a hundred atmospheres so that the D–T mass is characteristically in the nanogram range.

Reasonably symmetric illumination is attained with two beams to illuminate the target from opposite sides or with "clamshell" reflector optics to illuminate the target over much of its surface. A short pulse of energy—in the tens to hundreds of picoseconds—incident on the target causes the glass shell to heat rapidly and explode both inward and outward. The inward motion compresses the D–T fuel and raises its temperature to the point that thermonuclear neutrons are generated. This type of target is called an "exploding pusher" and is to be distinguished from "ablative compression" or "isentropic compression" targets discussed below.

The implosion of pusher targets is relatively easy to diagnose, because the fuel is strongly heated, giving off x rays and sufficiently large numbers of alpha particles and neutrons to be measured. For example, more than 10^9 neutrons have been attained with a laser input of a few terawatts. The extreme form of exploding pusher target is one in which all of the laser energy is incident on the target before appreciable shell expansion occurs. Though these targets are relatively easy to implode, calculation unfortunately shows that gains high enough to produce useful fusion energy can not be produced in them.

The type of target, called an "ablative-compression" or "isentropic-compression" target, is typically of the same diameter or larger than the exploding pusher, but with a shell that is thicker. The thicker shell serves two functions:

- It prevents high energy electrons from preheating the D–T fuel and
- it vaporizes and blows outward, causing an inward momentum transfer to the D–T fuel.

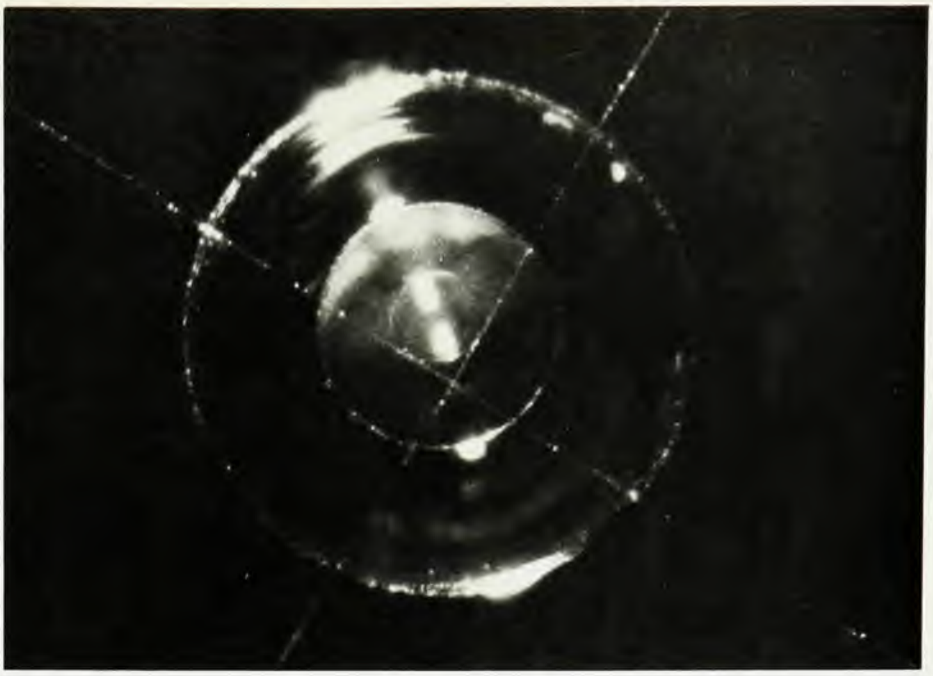
In contrast to the exploding pusher mode, the laser energy is incident on target during most or all of the time that the pellet fuel is imploded by the momentum reaction and is more effective in transferring larger amounts of inward momentum to the fuel. Therefore much higher compressed densities are achieved than in exploding pushers. Because electron preheat is smaller for ablative compressions, they attain lower final fuel temperatures than exploding pushers. Exploding pushers therefore tend to reach higher temperature and lower density than ablative compressions. On the other hand, with enough incident laser energy it is possible to attain greater burn efficiencies and thus higher pellet gains with ablative compressions. This is shown in figure 2, where gain is plotted as a function of power for both exploding pusher and ablative-compression targets. Ablative-compression targets can take several forms. Multilayer targets have been designed in which a low-atomic-number material serves as the outer-shell ablator. An inner shell of high-atomic-number material, such as gold, serves as the "pusher" or "tamper," which is driven inward by the ablative reaction; figure 3 shows such a multiple-shell target. This type of target may involve cryogenic layers where the fuel may be frozen as an inner layer on the pusher. In the latter case, the very center of the target may be a void.

In the case of ablative compression, careful driver pulse shaping may be required; the early laser-generated shocks through the pusher should be weak to minimize hydrodynamic preheat and the later shocks strong to produce a strong compression of the fuel. The requirements on pulse shaping can be lessened by tailoring the pellet structure in a multiple-shell configuration.

Target design and performance prediction is a difficult part of inertial-confinement-fusion research, involving complex computer codes. For optimal match of targets and laser pulses, the performance of the target as a function of shell mass, aspect ratio (ratio of shell radius to shell thickness) and initial densities of shells must be determined. This requires elaborate calculations of characteristic energies, time scales of hydrodynamic motion and of the properties of materials at high temperatures and densities never before observed in the laboratory.

Data from experiments are modeled extensively on two-dimensional computer codes that incorporate plasma physics of absorption, transport, hydrodynamics and D–T burn dynamics. Studies of plasma-physics phenomena and experimental target compressions have substantially increased prediction capability and allowed more realistic evaluation of the requirements for inertial-confinement fusion.

The greatest difficulty with more complex targets is in fabricating multiple layers with a surface finish of very high quality. Surface irregularities of more than 1% of the wall thickness appear to result in highly unstable compressions of thick shells. The shells composing the target must be highly concentric. If cryogenic fuel layers are required, the difficulties, now being resolved, of making such targets will be compounded by the problems of handling them in the target-chamber environment. Where void or gas-filled layers occur, the structures within must be supported, by some technique yet to be developed. Laboratories are developing the technology for making such targets with some degree of reliability.



A glass microballoon within concentric plastic and gold microshells. Such multiple-shell targets are expected to benefit both from the decoupling of outer-shell instabilities from the inner shell by the gas layer between the two shells and from velocity multiplication. The pellet shown is one of several target-design concepts that will be tested on lasers in the 10-kilojoule range with pulses of 1 nanosecond or longer. Figure 3

Clearly, the more advanced targets present a sharp contrast to the earlier and simpler exploding-pusher targets, for which pulse shape, irradiation symmetry and target-finish tolerances were much easier to satisfy. The lasers now available lack the energy required both to compress targets strongly and to heat the fuel mass sufficiently to produce large thermonuclear yields. However, lasers should soon become available which will have sufficient energy to drive ablative compression—a scientific milestone of great importance in the program. Beyond this, new combinations of improved target design, greater laser energy and more power on target will undoubtedly lead to improved understanding of the physics of target implosions and our ability to predict the scaling laws applicable to experiments at higher energy.

Laser development

In the early 1970's, there existed two lasers that appeared to have the capability for scaling to the high-peak-power, short-pulse regime required for inertial-confinement fusion. The two laser systems were neodymium-doped glass (Nd:glass), operating at 1.06 microns and carbon dioxide, with peak gain at 10.6 microns. Both of these laser systems were well studied, having been funded by the Department of Defense.

Of these two laser systems the CO_2 laser was, and still is, presumed to be suited for eventual power-plant applications because of its intrinsically high efficiency and the relative ease with which flowing-gas systems can be developed for high-repetition-rate operation. The Nd:glass laser system, in contrast, appeared to be limited to a research role, in which it had the advantage of demonstrated short-pulse operation and a wavelength ten times shorter than that of CO_2 lasers. The uncertainty surrounding the efficiency of long-wavelength radiation (much greater than 3 microns) to implode targets (coupling efficiency) made it desirable to pursue dual research efforts with both Nd:glass and CO_2 systems. A third laser-development program was begun, to identify and develop a high-efficiency gas laser system with wavelength less than 3 microns for use in the event that the CO_2 laser proved unsuitable for power-plant applications because of its long wavelength.

The development programs for Nd:glass and CO_2 lasers have met with a considerable degree of success. At the outset it was quickly discovered that Nd:glass lasers had severe limitations in power density (power/unit area) resulting from nonlinear interactions between the laser pulse and the transparent dielectrics through which it propagates (such as the laser glass, lenses and windows). Such a nonlinear interaction produces a high-spatial-frequency modulation on the propagating pulse. This diffracted energy reduced the focussable power from the system, appearing to limit Nd:glass laser development either to modest amplification or to ever larger optical elements to reduce the flux level through the system. Intensive analytical modeling of the Nd:glass laser system fortunately resulted in the development of a technology minimizing the impact of the nonlinear interaction. This permitted the design

The 10-kilojoule Eight Beam System shown here during assembly at Los Alamos consists of four two-beam modules in an array around the centrally located target chamber. This system uses the highest-power carbon-dioxide laser ever built. Its high energy capability will permit experiments in a region of pellet gain far beyond current levels. Figure 4

and operation of laser systems larger and more powerful than had been previously possible. Multiple spatial filters in a single laser chain repeatedly remove the high-frequency components of the pulse to prevent them from growing large enough to rob the system of focussable power or damaging the system's optical elements. The use of spatial filters, coupled with the development of ultraclean laser assemblies to reduce diffraction by dirt particles, has been essential to the design of laser systems such as the Argus and Shiva lasers at Livermore.

A recent remarkable success in further reducing the magnitude of the nonlinear interaction was the development of advanced optical materials with intrinsically reduced values of the nonlinear index of refraction. These materials permit even higher flux levels to be propagated in the laser pulse, enabling the laser designer to develop systems in the 300–600-kJ range with only modest increases in beam aperture and the number of laser-amplifier chains. For the details of many other technology advances that have accompanied the development of Nd:glass lasers through Shiva, the reader is referred to papers presented at the recent Topical Meeting on Inertial Confinement Fusion.[2]

The CO_2 laser system—in contrast to the Nd:glass laser—was already highly developed in the early 1970's. It delivered pulses of exceptionally high energy but at durations of hundreds of microseconds, making the peak powers unsuitable for inertial-confinement fusion. To develop CO_2 lasers capable of delivering their stored energy in a single short pulse on the order of a nanosecond required new techniques for isolating the gain in the laser amplifiers so as to prevent both parasitic oscillation and amplified spontaneous emission. Simple approaches to solving these problems failed due to multiphoton dissociation of absorber molecules at the very high intensity levels encountered in these CO_2 lasers. However, isolation techniques involving gaseous saturable absorbers have been developed and will be employed on the large CO_2 lasers under development at Los Alamos. Figure 4 shows one of these, the 10-kJ Eight Beam System.

What makes a good driver?

As in the case of Nd:glass lasers, numerous other supporting technologies have been developed as part of the CO_2-laser program. These technologies include the development of large-scale optics (focal length over 2 m) for use with the cylindrical amplifiers to be used in the Antares laser system as well as the cold-cathode electron gun required for excitation of the large amplifiers. The CO_2 laser program is also reviewed in the papers presented at the recent conference on inertial confinement fusion.[2]

Our ability to scale the Nd:glass and CO_2 lasers up to the high peak powers required to implode reactor-size pellets with substantial energy gain is reasonably assured. However, Nd:glass lasers could be made to operate with high average power only with the perfection of techniques that have not yet been demonstrated. Carbon dioxide lasers, while efficient as lasers, may yet turn out to be relatively inefficient as drivers of fusion pellets if the effectiveness for pellet compression and heating decreases too rapidly with increasing wavelength. We can therefore specify a set of requirements for a laser-fusion driver:

- it should be a gas, which can be readily cycled to cool the medium, and
- it should have a short wavelength. Indications are that a laser in the visible part of the spectrum would have better pellet-driving characteristics even than neodymium–glass, although multiple-photon absorption in transparent optical materials would probably set a lower limit on tolerable wavelength of about 300 nanometers.

Should wavelength not be a problem, there is no better laser candidate now than CO_2. If the wavelength dependence is not strong in the 1–3 micron range, hydrogen fluoride will be a strong candidate among the lasers already under development. Finally iodine, which has a wavelength near that of neodymium, could become a strong candidate if a considerably more efficient pumping technique than flashlamps is developed for it.

The candidate lasers in the visible region, plus iodine, are listed in the table on page 56, along with brief characterizations of the key technical issues relating to each. An occasional criticism of the inertial-confinement-fusion program—that it has an interesting concept but no laser that could make it a viable energy source—appears in a different light when this range of lasers is considered.

Most of them are "storage" lasers; like Nd:glass and CO_2, they are pumped for relatively long times (on the order of microseconds) and then the energy is extracted in a comparatively short time (pulses of a nanosecond or less). However, the HF laser and the KrF-pumped Raman-pulse-compression laser would be high-gain lasers. To control amplified spontaneous emission and parasitics, high-gain lasers must have a saturating optical field present during the pump time; that is, quasi-cw lasers. Sophisticated optical extraction techniques will be required for the high-gain lasers, either optical pulse compression or angular multiplexing, in which beams make multiple passes through the lasing medium at slightly different angles and times.

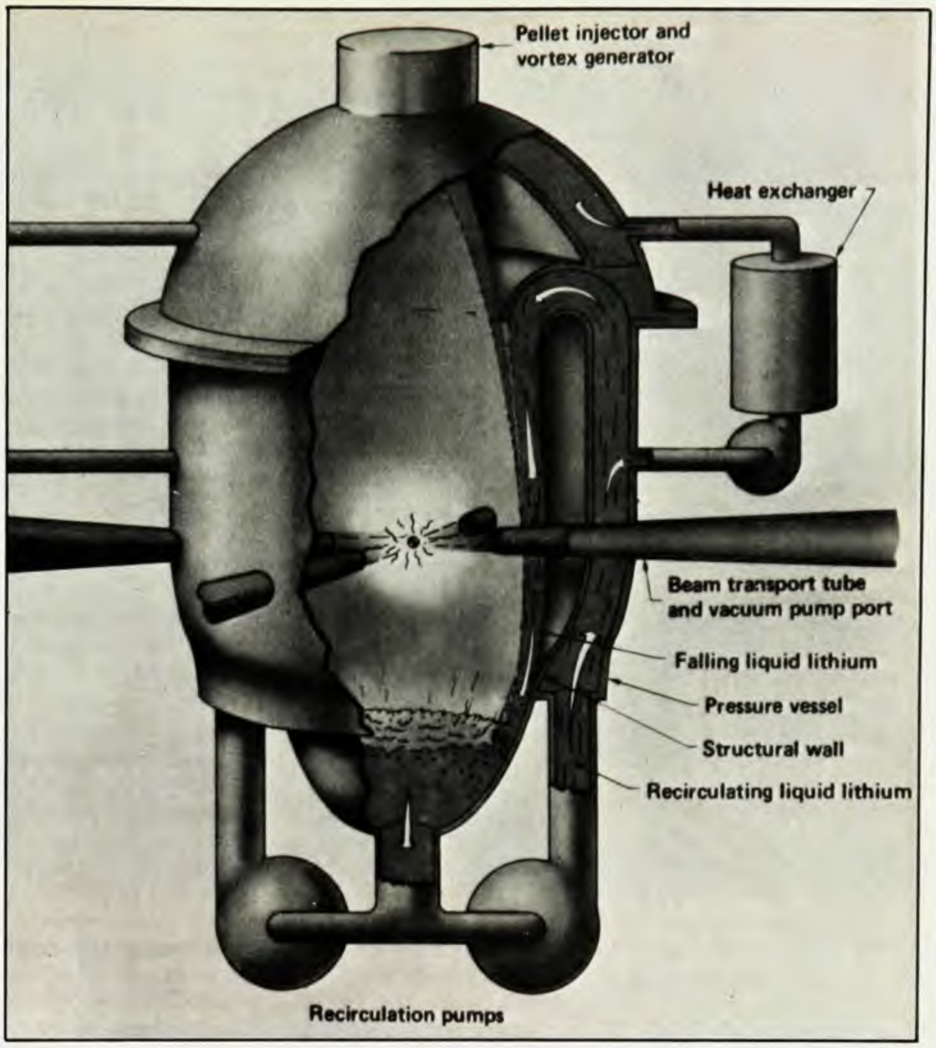
In the works

The present program plan is to develop one of the candidate advanced lasers to the 1-kJ level by the end of 1981 and, if this is successful and an alternative to CO_2 is required, to develop by 1985 a 30-kJ module that will operate at a modest repetition rate on the order of 1–10 pulses per second.

Meanwhile, the major target experiments in the program will continue to be performed on medium-wavelength Nd:glass and long-wavelength CO_2 lasers of increasing peak power levels as these become available. The major commitments of the program now are to build and operate by 1984 the Antares 100-kJ CO_2 laser at Los Alamos and the Nova 300-kJ Nd:glass laser at Lawrence Livermore.

The Department of Energy is supporting the phased development of the Omega Nd:glass laser at the University of Rochester's Laboratory for Laser Energetics. The six-beam Zeta system will be operated at Rochester late this year at the 3-terawatt level. Smaller Nd:glass lasers are being used for laser–matter interaction experiments at the Naval Research Laboratory and for target design and experimentation at KMS fusion.

The major programs abroad (in Japan, the USSR and France) also are developing Nd:glass and CO_2 lasers in parallel, the former as the main experimental tools and the latter as the best candidate laser for eventual energy applications. A number of other countries—notably the UK, Federal Republic of Germany, Israel and Canada—have significant but smaller programs in basic experimentation and laser development.



The lithium-fall cavity concept from the Livermore Laboratory relies on a falling curtain of liquid lithium to collect the energy released and transport it to the heat exchanger, breed tritium by absorbing the emitted neutrons, and protect the structural walls of the reactor. The relatively long times required to remove the lithium vapor after each microexplosion will limit this scheme to low repetition rates; it may therefore require large pellet yields. The simplicity inherent in the point geometry of the inertial-fusion microexplosion allows a high degree of flexibility in cavity designs to contain it, but provision for beam entry, pellet injection and tritium techniques is required for all designs of inertial-fusion systems. Figure 5

Particle-beam development

The development of pulsed power-accelerator technology for fusion experiments has sought to take advantage of the high fields in dielectrics (typically 10–100 MV/m), attainable for short pulses and low costs (on the order of \$10–20 per joule). This goal has been met primarily for single-pulse accelerators used initially in the weapons programs of the Atomic Energy Commission and the Department of Defense. Since the beginning of a pulsed-power-accelerator program for fusion at Sandia in 1973, the Hydra (0.1 TW), Proto I (2 TW) and Proto II (8 TW) accelerators have been developed for target experiments. They also test beam-formation and focussing concepts required to make this technology a serious contender for use as a fusion driver.

Electron beams have been observed to self-focus, "pinch," at very high currents, due to the effects of the magnetic field of the electron beam itself. "Pinch" currents up to 10^7 A/cm^2 have been achieved. Experimentally beams have been focussed on fuel pellets 10–100 times as large as those used in experiments with lasers of comparable power, because of the longer electron-absorption depth and the availability of higher beam energies. Actual thermonuclear burn has been difficult to induce so far.

Pulsed power accelerators of electron beams were originally conceived of as efficiently focussing beams within the diode. This in-diode approach generally relies on the use of hollow electrodes and, in many experiments, the injection of a plasma into the target region to serve as an anode to focus the beams. Clearly only very small pellet explosions could be practical in the diode without severe damage to the machine. An additional difficulty arises from enhanced ion-current generation in the self-pinched electron flow: The configuration most desirable for self-pinching also enhances energy losses through ion-current generation in the direction opposite to the electron beam flow. Reduction in the ion current can be brought about by increasing the voltage, and higher values of ρR can be achieved by suitable pulse shaping. However, higher voltage can bring with it breakdown in dielectrics or in vacuum. The problems with using higher voltage, as well as the limitations of the pinch effect and potential diode damage, all argue for a design based on transport of multiple beams to the target.

The immediately practical scheme, successfully demonstrated in 1976, makes use of fine wires to define the paths of 50-kA discharges in air at atmospheric pressure; the focussed beams propagate efficiently and in a stable fashion over at least 1 meter in the channels formed by the discharge. The final overlap of multiple beams in channels has not yet been demonstrated. However, the technique appears to be workable and could lead to beam transport at a distance with techniques more suitable to reactor operation, for example, the use of low-power laser beams to form the channels. The transport of the high-voltage pulses from the generators to the diodes also presents a moderately difficult problem.

The latest methods employ multiple, magnetically insulated vacuum transmission lines to carry high-current pulses from capacitor banks to single or double diodes. This permits the rather bulky capacitor banks to be located an additional 5–10 m away from the diodes.

Electron-beam deposition in targets has been shown to be significantly enhanced at current densities greater than 1 MA/cm^2. The electron stopping distance is much shorter as a result of the beam self-magnetic field penetration into the deposition region. The effect of magnetic deflection is that the electrons pass several times through the ablator shell of the target, which for this purpose should be a low-Z material such as plastic or glass. Enhanced deposition has been observed with targets shot on Proto I using a 1-TW beam. However, in these target experiments the temperatres attained were too low to result in measurable neutron yield. The first substantial neutron yields are expected from Proto II experiments this year.

A more complex target concept employs a fine filament of deuterated polyethylene in a very thin shell target. The filament is exploded by means of a prepulse, preheating the fuel and generating a magnetic field to form a magnetic barrier to thermal conduction. As a result it is possible to reach higher final fuel temperatures with a lower compression ratio; the imploding shell compresses the preheated central region to a higher temperature than it would have without preheat. Auxiliary experiments using different designs have clearly shown that magnetic thermoinsulation was necessary to the success of these targets, which achieved 10^6 neutrons with a 0.25-TW beam. This target approach is expected to permit the use of longer pulses, on the order of 100 nanosec. Scaling of these targets to higher power will be studied later in 1978.

Ions—light and heavy

Interest in light ions for driving targets is increasing rapidly. This arises from calculations showing that the power required for ignition of thermonuclear burn can be reached at lower currents and higher voltages than with electrons. Primarily because of inductance problems it is much easier to build the higher-impedance proton accelerator than the low-impedance electron accelerator. Hence, even if power requirements were the same in the two cases, the accelerator design problems appear to be less severe for ions.

Ions have advantages in energy deposition in a target:

- Ions are expected to lose their energy most rapidly near the end of their path through a target shell, so that the peak energy deposition occurs deep within the target shell.
- Ions produce virtually no bremsstrahlung during their slowing down, so excess preheat of the fuel mass is not a problem.
- Ions will not backscatter appreciably from a target surface.

These desirable deposition characteristics may reduce the ignition power requirements for ion-driven targets by a factor as much as 5–10 below requirements for electron-driven targets.

The Sandia program, complemented by continuing efforts at Cornell University and the Naval Research Laboratory, has essentially demonstrated that the theoretically predicted high efficiencies of ion production can be achieved by several methods, but issues of beam focussing and transport are far from resolved. These include the formation of virtual electrodes, use of plasma sources for charge neutralization and creation of high-density plasmas as ion sources. The first scaling steps at high voltage are to be made on the Hermes accelerator at 10 MV and with external fields. Studies of self-pinching, using the electron-beam accelerator approach but with the polarity reversed, will be made on Proto I and Proto II.

Even greater interest is currently being shown in heavy ions.[3] These particles also have short, well defined ranges in target materials. More important, there is a mature technology from which extrapolations can be made to fusion requirements. Target calculations made at Lawrence Livermore Laboratory indicate that pellets for commercial reactors could be designed for ion beams of 1 MJ energy and 100 TW peak power.

A pilot fusion reactor, with heavy ions driving pellets, would be expected to employ some combination of the following major subsystems:

- rf linacs (including ion source and one or more pre-accelerators),
- synchrotrons,
- accumulator (or storage) rings
- induction linacs, and
- final pulse compression and transport to target.

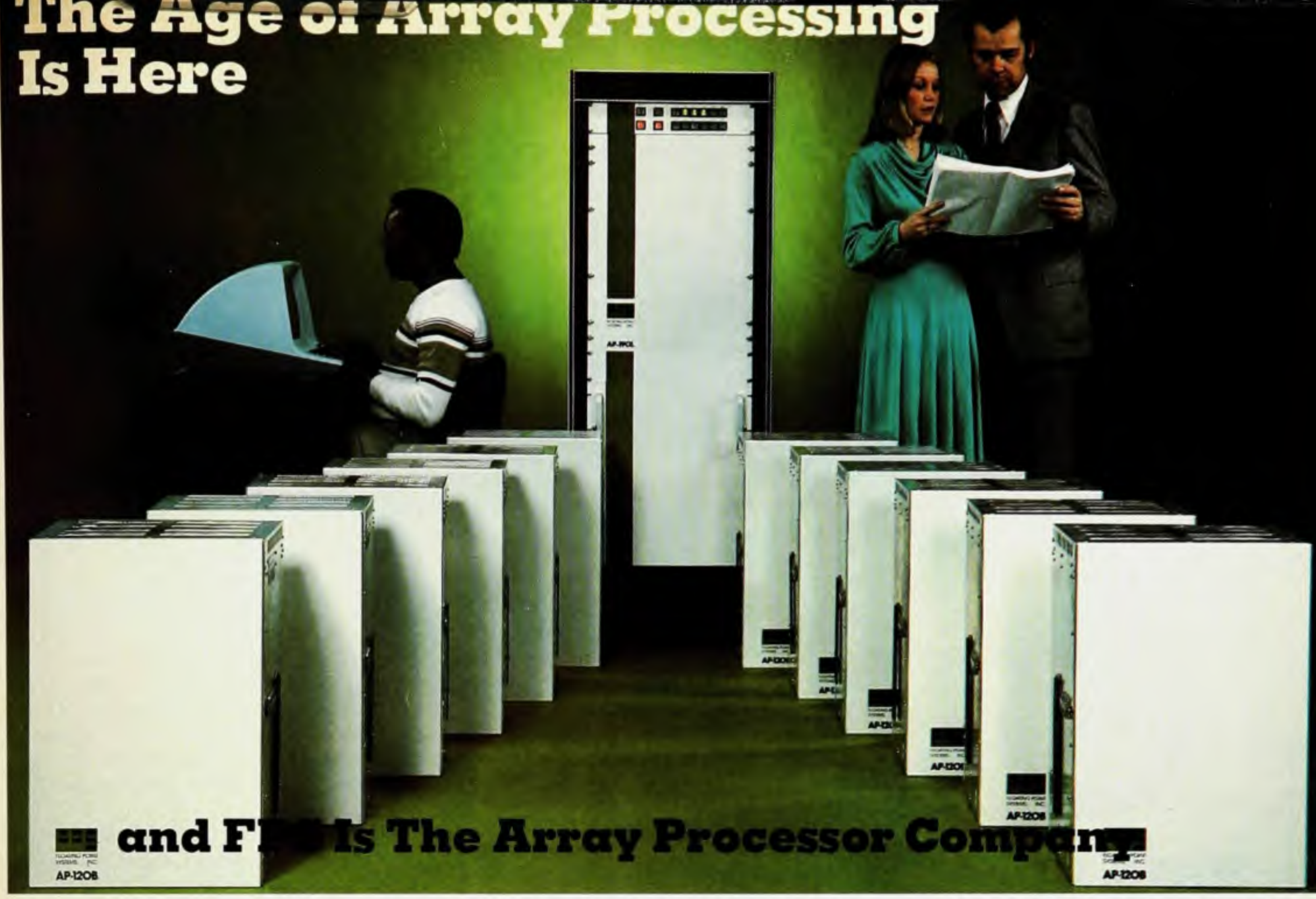
The "Search and Discovery" story in the February issue of PHYSICS TODAY (page 17) contains further details on this method.

Groups in three DOE laboratories are using pellet-design calculations performed at Livermore to develop conceptual designs for such a pilot reactor driver. The accelerator design groups are at

- Argonne, concentrating on a system consisting of an rf linac driving one or

Candidate advanced lasers

Laser	Pump	Wavelength (microns)	Projected system efficiency	Key issues
			Group VI	
Sulfur S(^{1}S)	Kr_2^* (electron beam excited)	0.459	1–4%	Kr_2^* driver efficiency, S(^{1}S) photoionization and destruction
Selenium Se(^{1}S)	Xe_2^* (electron beam excited)	0.489	1–4%	Xe_1^* driver efficiency, Se(^{1}S) photoionization and destruction
			Metal vapor excimers	
CdHg	Electron-beam sustained discharge	0.47	10–15%	Excited-state absorption; technology difficulties
Hg_2	Electron-beam sustained discharge	0.335	10–15%	(high temperature, corrosive materials)
			Rare-gas halide lasers: Raman pulse compression	
CH_4	KrF (e-beam sustained discharge)	0.268	5–9%	Other nonlinear scattering processes caused by high intensities
Tl	KrF (e-beam sustained discharge)	0.308	5–8%	
Direct short pulse extraction KrF	e-beam sustained discharge	0.249	10%	Optical systems engineering
			Rare-gas halide lasers: Resonant excitation of solid-state systems	
Tm:CaF_2, Tm:glass	XeF (e-beam sustained discharge)	0.450	2–3%	High Tm concentrations required causing heat loading problems which may limit repetition rate
Tm:YLF	XeF (e-beam sustained discharge)	0.450	2–3%	Heat loading
Ho:YLF	KrF (e-beam sustained discharge)	0.283	4–6%	Heat loading
			Rare-gas halide lasers: Optical pumping of storage media	
HgXe	KrF (e-beam sustained discharge)	0.27	3–7%	0.249 absorption in wings of Hg line
			Existing lasers	
HF	Electron beam	2.7	5–10%	Short pulse extraction
Iodine	Flashlamps	1.32	1–2%	Pump efficiency and chemical recovery



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ARRAY PROCESSOR COMPUTER
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more synchrotrons, which in turn feed several accumulator-storage rings;

- Brookhaven, concentrating on using rf linacs brought to full energy, followed by a number of accumulator-storage rings, and
- Lawrence Berkeley Laboratory, which is concentrating on the induction linac.

The effort in system design is, however, somewhat independent of the near-term R&D program. The ion source, preaccelerator and space-charge-theory efforts now being conducted are required for all the system designs.

The next step, beyond the initial design work and basic experiments now under way, is a feasibility demonstration experiment, now dubbed HIDE (Heavy Ion Demonstration Experiment) and scheduled to be completed by 1985. At 100 kJ and 3–30 TW, HIDE is to be a machine based on a subset of one of the designs now being studied. It would operate at 0.1–1 pulse per second. These parameters are considered sufficient to perform pellet scaling experiments to confirm the predicted coupling of heavy ions to matter.

A hybrid reactor

A timely possibility for early introduction of fusion power is the fusion–fission breeder. Any fusion reactor could be used as a basis for the hybrid, which can be defined as a subcritical fission reactor that is driven and controlled by an internal source of high energy neutrons from a fusion burner. However, inertial-confinement-fusion devices offer flexible geometry and sizing, compatible with current fission reactor technology.

Studies have shown that a hybrid fueled with depleted uranium (tailings from conventional separation processes) could produce enough fissile material to fuel more than six light-water reactors of equivalent thermal power. Hybrids could also operate on a thorium cycle, and techniques of operation have been advanced that could strongly reduce the proliferation dangers associated with large-scale reprocessing of used fuel elements. From the point of view of fusion R&D, the most interesting aspect of hybrids is that they could operate effectively at modest energy gains, which are likely to occur much sooner than high gain.

The hybrid option would offer an application attainable with drivers of lower efficiency, lower reliability, and with lower pellet gain than would be required for pure fusion. Already the Soviet Union is working on a scheme to develop, around the electron-beam driver that now exists as a 1-TW module, a 5-MJ–100-TW electron-beam machine of sufficient energy and power to meet reactor requirements as now known by the mid-1980's.

Actual energy production from inertial-confinement fusion is plainly still a long way off in the future. The uncertainties about confirmation of the feasibility of microexplosions in pellets, with net energy gain induced by laser or particle beams, will not be available before the mid-1980's.

Outlook

Systems studies have outlined the range of the engineering problems to be solved, and have identified key issues about reactor and plant design.[4] A number of conceptual reactor designs have been developed to accommodate varying sizes of explosions, corresponding to gains from targets ranging from moderate to very high, breed tritium to be recycled into targets, accomplish wall protection and heat transfer, and protect final optics (in the case of lasers) or final focussing elements (in the case of particle beams). Figure 5 shows a new concept for containing very-high-yield pellet implosions, the lithium-fall reactor cavity under study at the Lawrence Livermore Laboratory. With some reasonable assumptions about our ability to develop large-scale inertial-confinement-fusion systems, we are on a development path that is consistent with several possible energy futures.

The development of electrical power-generating plants based on pellet fusion is clearly the longer-term option, because the product of driver efficiency η and pellet energy gain Q are high. With η about 5–10%—a reasonable goal for some of the lasers now under development—pellet-energy gains of 100–200 would probably be required for economical energy production.

Intensive fusion research in recent years has uncovered no serious obstacle to proving feasibility for several approaches. By the early to middle 1980's the important results on feasibility demonstrations for both magnetic and inertial-confinement fusion should be in hand. A major national commitment to develop fusion systems as a national energy resource can not wait much longer than that to meet national needs.

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