Laser Fusion: A New Approach to Thermonuclear Power

If the fusion of hydrogen that takes place in the sun could be controlled on earth, seawater could provide fuel for the world for a million years or more; but no device for controlling fusion has been proved feasible yet. Most of the effort and money for U.S. fusion research for the last 20 years has been directed toward the goal of containing a fusion reaction with magnetic forces, but many scientists now think that the goal of achieving fusion with high-powered lasers could be reached first.

After Russian researchers first demonstrated in 1968 that a laser could initiate a fusion reaction, many countries expanded their laser research programs. But the size of the lasers needed for a practical power plant had been considered impossibly large until the U.S. Atomic Energy Commission (AEC) last November revealed details of a new laser method that had previously been classified. Instead of heating a pellet of hydrogen isotopes with a single laser beam, as assumed in most older calculations, many beams from different directions will heat the pellet in such a way that it is greatly compressed. The advantage of the new scheme has so far been demonstrated only in computer simulations; but if the predictions are borne out in experiments, large lasers under construction now (in the Soviet Union), or planned for construction within the next year or two (in the United States), could prove the scientific feasibility of the principle.

Demonstration of feasibility of laser fusion in 2 to 4 years as predicted by some scientists would be dramatic in comparison with the slow progress of magnetically confined fusion. However, research on magnetically confined fusion is much more advanced, in the sense that there is a long history of comparison between experimental results and theoretical predictions. The big lasers necessary to test the feasibility of laser fusion are just now becoming available, and much more development will be required to perfect lasers for a practical power plant. Designs for the power plant itself are in the most rudimentary form. Since there is no conceivable way in which the materials in a fusion reactor could combine to yield a nuclear explosion, the principal environmental problem is expected to be the confinement of tritium, a major radioactive by-product that is quite volatile. The first generation of fusion power plants would almost certainly use steam turbines to generate electricity, so the extent of thermal pollution would be about the same as for fossil or fission fueled plants.

The general outline of the laser fusion process is that a small, well-focused spot of laser light very rapidly heats up a small pellet of deuterium and tritium to temperatures hot enough to ignite fusion (100 million degrees C) before the pellet has expanded significantly. Because Newton's law of inertia basically determines the speed of expansion (about 10^6 meters per second), laser fusion is often called inertially confined fusion. A 1-millimeter pellet expanding at 10^6 m/sec would double in size in 1 nanosecond (10^{-9} second), so the laser energy must be delivered very rapidly.

Research directed toward laser fusion is proceeding along two parallel paths, with very little interaction between them so far. The theoretical efforts have consisted of computer simulations of the complicated physical effects that take place when a laser interacts with a fuel pellet. The experimental efforts, in the United States at least, have been concentrated on the development of powerful lasers capable of delivering their energy in less than a nanosecond. Because the focusing and timing characteristics of neodymium glass lasers are superior to other types of high-powered lasers, most efforts have been oriented toward developing the neodymium instruments.

The Soviet Union has the largest research program for laser fusion—it is estimated to be twice the size of the U.S. program—but the U.S. program has recently been enlarged. The federal budget requests for laser fusion research have almost doubled in the last year, from $13 million in fiscal year 1972 to $23 million in fiscal year 1973, and are expected to increase again in fiscal 1974. Intensive programs of research are being mounted at the Lawrence Livermore Laboratory and the Los Alamos Scientific Laboratory. In addition, private sources are supporting laser-fusion research at the University of Rochester, where the university, General Electric Company, and Esso Research and Engineering Company are supporting a program that will cost $1 million in 1972, and at Ann Arbor, Michigan, where a company named KMS Fusion is planning to spend $50 million over the next 4 years. Although the hope and enthusiasm of the private sector is for an early demonstration of practical fusion power, the focus of the AEC research, which is administered under the Division of Military Applications, is not yet differentiated between military and civilian goals. One possible military application is a "pure fusion" thermonuclear weapon—that is, one not requiring uranium or plutonium.

The novel concept that has made many scientists more optimistic about the eventual success of laser fusion is an implosion process, by which the fuel pellet is compressed so that it burns much more completely. When several laser beams hit a pellet from many sides, the outer portion ionizes, heats up, and blows off at high velocity to produce large pressures in the center of the pellet. According to John Nuckolls and Lowell Wood at the Lawrence Livermore Laboratory, Livermore, California, the laser energy required for a practical power reactor could be reduced by a factor of 1000 from previous estimates, to a value of 10^5 or 10^6 joules. However, this is still much more than the energy of the largest laser available today, a nine-path neodymium laser developed by Nikolai Basov and his co-workers at the Lebedev Institute in Moscow. This Soviet laser delivers 600 joules in 2 nanoseconds.

In experiments to date the amount of fusion energy released has been much less than the laser energy, but Nuckolls and his colleagues estimate that a fusion reaction that exactly replenishes the energy of the laser light could occur at 10^3 joules. This balance of energy, called "break even," is normally referred to as the criterion for judging the arrival of laser fusion at the point of scientific feasibility. It may be a deceptively easy milepost to reach, however, because typically only 0.1 percent of electrical energy expended to operate a neodymium glass laser emerges in the energy of the light emitted.

While the achievement of break even may not herald the imminent arrival of practical laser fusion, most observers agree that experiments at break even power levels are exactly what is needed to check the difficult calculations of laser-pellet interactions, and to learn which of the many possible physical mechanisms will be most important. Details such as the amount of heating and compression can only be predicted from highly nonlinear calculations, which have uncertainties whose cumulative effects may be quite large.

Most diagnostic information about the physical mechanisms of the laser-pellet interaction has been obtained from measuring the amount of reflected laser light and the number of neutrons produced in fusion, both of which are relatively primitive measures of the interaction (some scientists think that the information about neutron yields is almost useless). Apparently none of the U.S. experiments have used a laser configuration that could produce an implosion. French scientists at Limeil have a four-path laser that will produce 150 joules on a deuterium target, but most observers believe that only the group at the Lebedev Institute currently has the capability to begin testing the implosion theories. A 27-beam laser under construction there is supposed to produce about 10^4 joules and may be the first instrument to achieve a break-even reaction.

The research programs at different U.S. laboratories can be approximately characterized as those that emphasize timing variations and those that emphasize wavelength variations. Researchers at Livermore and at KMS Fusion attempt to maximize the compression by time-tailoring the laser pulse very carefully. In some cases a small precursor pulse is used to create a thin plasma on the outside of the pellet. Certain effects in the thin plasma increase the symmetry of the implosion, so that high pressures can be reached.

Researchers at the Los Alamos Scientific Laboratory, the University of Rochester, and Sandia Laboratories (as well as those at Livermore) plan to experiment with wavelengths different from the near infrared radiation of a neodymium laser [1.06 micrometers (μm)]. Computer simulations of plasmas, performed at Livermore and Limeil, indicate that radiation at wavelengths shorter than 1 μm may be desirable for fusion. Shorter wavelength laser pulses are absorbed much deeper in the pellet, and thus are more effective in generating an implosion.

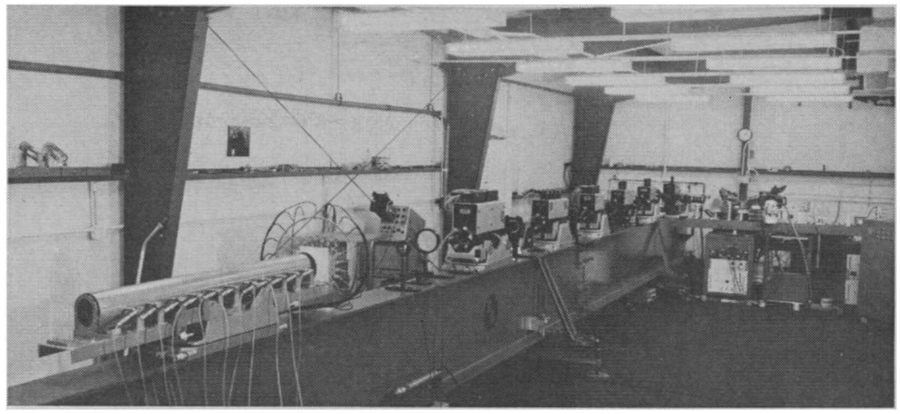

Fig. 1. The neodymium glass laser at the Naval Research Laboratory, Washington, D.C. This laser, which produces a light pulse with 215 joules of energy in 0.2 nanosecond (about 10^{12} watts of power), is one of the largest lasers which the United States admits to having and which emits pulses short enough for laser fusion research. Similarly large lasers are in operation at the University of Rochester and at the Lawrence Livermore Laboratory.

Although neodymium lasers are excellent sources of powerful short pulses, most observers doubt that they could ever be used to drive a power plant because of their poor efficiency. Moreover, few scientists believe further development will do better than to double that efficiency. Neodymium lasers are also difficult to operate at high repetition rates but scientists at both Livermore and Los Alamos estimate that fast repetition rates (one shot per second or greater) will be needed for a useful power plant. At the current state of technology, the durability of neodymium systems is also far too poor to be practical.

One alternative is a carbon dioxide laser that appears capable of delivering high-powered pulses in a sufficiently short time with an efficiency of 10 to 20 percent. Although the largest energy that a CO_2 laser has delivered in a 1-nanosecond pulse is 8 joules, achieved with a prototype device at Los Alamos Scientific Laboratory, Keith Boyer and his associates there expect to have a 1000-joule unit ready for operation by mid-winter. It may be difficult to achieve pulses as short as a neodymium laser can produce, but Boyer is confident that 0.25-nanosecond pulses can be achieved with known techniques. Boyer estimates that the largest feasible energy from a single-path CO_2 laser will be 2000 to 5000 joules, somewhat larger than the estimates of 1000 to 2000 joules for a single-path laser of glass media. Of course by using more than one single-path laser, the total energy could be multiplied manyfold.

The greatest limitation of the CO_2 laser, however, may be that its very long wavelength radiation, 10.6 μm, will not heat a pellet very efficiently. Computer simulations indicate that the 10.6-μm radiation will create a surplus of very hot electrons that may preheat the central pellet mass so that it would be difficult to compress, or may simply not transfer energy to the pellet at all. No studies of laser-pellet interactions have been done with CO_2 radiation yet. Boyer and his co-workers think at the moment that the best way to get an efficient laser at a shorter wavelength would be to convert the frequency from a CO_2 device.

The detailed discussion of the merits of neodymium versus CO_2 lasers, which is currently going on among the various members of the AEC program, may ultimately be superfluous to the merits of laser fusion. Not only are the major points of the debate derived from theoretical calculations which have not been experimentally tested, but also new breakthroughs in laser technology may provide an acceptable laser at the right wavelength, whatever that turns out to be. According to John Emmett, who now heads the Laser Research and Development program at Livermore, breakthroughs have occurred in laser technology at the rate of almost one major innovation per year, and there are 20 to 30 systems similar to the CO_2 system which might develop into efficient lasers. An example of a new high pressure gas laser with a short wavelength that shows great promise, Emmett pointed out, is that researchers at Livermore have recently succeeded in operating a high pressure xenon laser which emits 0.16-μm radiation and could theoretically function with 90 percent efficiency.

Few studies have been made of the engineering design for fusion reactors because so few of the design criteria can be established yet, and the studies that have been made emphasize general features. Some problems will be common to both magnetically contained and inertially contained devices because a deuterium-tritium (D-T) mixture appears certain to be the fuel initially used in both processes. The reactor size will be determined in many respects by the need for a layer of lithium, 1-m thick, to absorb the high energy neutrons that will be produced in the reaction [neutrons with energies of 14.4×10^6 electron volts (14.4 Mev) will be produced in a D-T reaction, whereas neutrons from fission have an energy of only about 2 Mev]. Because the natural abundance of tritium is very small, new tritium must be produced by nuclear reactions in the lithium blanket and then collected to replace what is burned. However, tritium is radioactive, can replace hydrogen in any molecule, and will have to be handled carefully so that it doesn't come into contact with any water supply. These problems will be discussed in more detail in a later article on the energy potential from magnetically contained fusion devices.

Several engineering problems are specific to the laser-pellet fusion scheme, however. Besides a laser of great durability, which is certainly the foremost problem, a very strong restraining wall will be needed to contain the blast. Spherical steel vessels can be made thick enough to withstand relatively small explosions of 10^9 joules (the equivalent of 500 pounds of TNT), but some method must be found to contain the lithium and protect the structural parts against radiation damage. A study of laser reactor feasibility carried out at Los Alamos (*1*) suggests that the problem can be solved by building a double-walled enclosure with liquid lithium between the walls. If the inner wall is perforated, liquid lithium will flow through to cover its inner surface and the layer of liquid will protect it from erosion by x-rays and exploding pellet material. The reservoir of lithium (in which neutron energy is converted to heat) is large enough to assure a constant flow of heat to a steam turbine even though the fusion bursts are intermittent.

A laser reactor design which also uses liquid lithium as the primary absorbing medium for the fusion energy has been proposed by Art Fraas and colleagues at the Oak Ridge National Laboratory (*2*), but the Oak Ridge concept eliminates the need for an inner wall by swirling the lithium at a sufficiently high velocity to maintain a free-standing vortex. Fuel pellets will be injected into the vortex and ignited when they reach the center of the chamber. The Oak Ridge group also proposed to cushion the restraining vessel against the blast pressure by introducing fine bubbles of inert gas into the circulating lithium.

Both reactor designs are spare-time efforts, since the outstanding question is still whether laser fusion is feasible or not, and there is considerable difference of opinion among various investigators about such basic questions as the ideal size of the pellet. Nuckolls and his co-workers at Livermore favor a millimeter pellet, releasing about 10^7 joules of energy, whereas a pellet about 1 centimeter in diameter is selected by the Los Alamos report, as well as by researchers at Oak Ridge and Rochester. Although it may be possible to burn more of the larger pellets, more laser energy would be required to ignite the fusion reaction, thus exaggerating the gap between the lasers available and the lasers needed. For the smaller pellets, the value of the energy released would only be about 1 cent, if sold as electricity. Clearly one of the problems for economic feasibility is to produce pellets cheaply.

Technical Problems

If both laser fusion and magnetically confined fusion should be proved feasible, some aspects of the laser-based reactor would seem attractive. Most studies estimate that the size would be about 50 to 200 megawatts of electric power, much smaller than the estimated 500- to 2000-megawatt capacity of a Tokomak fusion reactor. The laser system would be a suitable size for ship propulsion, for instance. Many small units could be clustered together—perhaps served by a single laser system—or small units could be distributed geographically to provide electrical power for homes and industries. If many units were combined in a modular system, individual units could be shut down for replacement of parts damaged by radiation without significantly affecting power generation. According to Art Fraas, it appears that both the capital costs and the development costs would be lower for a laser fusion reactor.

But laser systems have been much less thoroughly studied than magnetic systems, and may seem to have fewer problems only because the concept is newer. According to the estimates of some knowledgeable observers, the technological problems of the laser alone could prove to be as difficult as the development of an entire Tokomak reactor. Certainly, the achievement of energy levels of 10^5 or 10^6 joules is difficult, and after that the problem of increasing the repetition rate to one shot per second may seem even tougher (the repetition rate of the NRL laser is about one shot every 4 minutes!) In order to keep the laser from being damaged during a pellet explosion, disposable mirrors or liquid metal mirrors have been suggested (to eliminate all straight paths between the pellet and the laser), but no tests have been made. Neither the Oak Ridge nor Los Alamos reactor designs seem to be particularly well suited for multiple-beam irradiation of the pellet, though presumably many variations are possible.

As an ultimate resource, the energy available from fusion is only surpassed by the resource of sunlight, which, after all, is just fusion power from a far greater reservoir. Of the several possible fusion cycles, the D-T fusion cycle is the only one even remotely limited by resources because the earth's lithium would have to be mined in order to continually manufacture more tritium. But, according to the Los Alamos report, the known world lithium resources are great enough to supply energy needs for 1 million years, even if the world population stabilizes at 10 billion people and the per capita energy consumption is equal to the U.S. rate in 1970.

Although the implosion concept of laser fusion is very appealing, the number of technical problems that can be foreseen appears to be immense, even if the "physics" is found to be favorable. By bypassing the need for a magnetic field, the laser approach has also bypassed a long and depressing catalog of plasma instabilities that have thwarted the enthusiastic early hopes of physicists for proof of feasibility. But more than one major breakthrough per year in laser development may be necessary before scientists can make hydrogen in a reactor hotter and denser than the sun.—WILLIAM D. METZ

References

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