search & discovery

AEC opens up on laser fusion implosion concept

Interest in laser-produced thermonuclear fusion is increasing rapidly. Until recently almost all discussion in the open literature mentioned only the possibility of using the laser to heat a fusion-fuel pellet, and most observers argued that the laser energy requirement for a fusion reactor would be impracticably high.

In November, in testimony before the Joint Congressional Committee on Atomic Energy, Robert Hirsch (then in the AEC Division of Research), revealed that the laser could also be used to cause an implosion of the pellet. This was apparently the first AEC announcement of the hitherto classified concept.

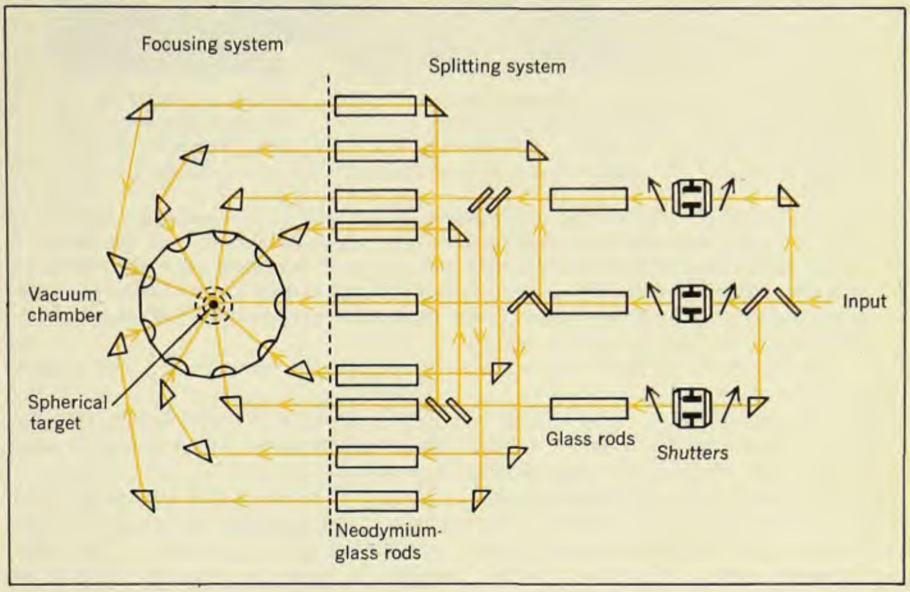
The following month, at the annual meeting of the American Association for the Advancement of Science, John Nuckolls and Lowell Wood of Lawrence Livermore Laboratory discussed calculations indicating that the laser energy requirement could be reduced by many orders of magnitude if the pellet were imploded to very high densities.

In April Keith Brueckner, vice-president of KMS Fusion, a subsidiary of KMS Industries, gave a talk at the University of Michigan revealing his previously classified calculations of laser-produced implosions. In May, at the Quantum Electronics Conference in Montreal, workers from many laboratories gave reports related to laser-produced fusion. Also in May AEC further declassified the program, although most of it remains classified.

So far there has been no experimental observation of laser-produced implosion, but some experts believe that workers at the Lebedev Institute in Moscow, under Nikolai Basov, are doing implosion experiments right now with their nine-path laser, which delivers 1300 joules in 16 nanosec and 600 joules in 2 nanosec onto a pellet. The Soviet group is apparently two to three years ahead of the rest of the world in development of the type of large lasers needed to implode fusion fuel to efficient thermonuclear burn conditions.

Theory. The work reported in Ann Arbor by Brueckner and in Montreal by the Livermore workers (Nuckolls,

continued on page 18



Nine-path laser at Lebedev Institute produces 1300 joules in 16 nanosec and 600 joules in 2 nanosec. The beam is split into three parts, each of which is then amplified by a rod. Then each beam is again divided into three, and each is again amplified. The nine beams than converge onto a single target. A 27-beam laser, now being constructed by the Soviet group, is expected to yield 200 joules in 2 nanosec.

The case of the missing solar neutrinos

The Brookhaven solar-neutrino experiment, after five years of running, is in even worse disagreement with theoretical expectations than it was earlier. While the theoretical value has tended to rise slightly, the experimental limit has dropped and is consistent with zero.

At a conference on neutrino astrophysics held near Budapest in June, Raymond Davis reported the most recent upper limit on the solar neutrino flux—less than 1 solar neutrino unit (1 SNU = 10^{-36} sec^{-1} per target atom). His limit reported in 1968 was less than 3 SNU, and so was his limit reported in 1970. However, some experts say that they will remain somewhat skeptical of the technique, beautiful as it is, until Davis has demonstrated that he can collect argon produced in a beta interaction, for example, Ar^{36} from the decay of Cl^{36}.

Theory. As John Bahcall (Institute for Advanced Study) says, Davis's value is "just not a socially acceptable number in solar-evolution circles. That's a number that cannot be reconciled with the standard theory of stellar evolution," which predicts a lower limit on flux of 1.7 ± 0.3 SNU. This limit would prevail if you assume the decay of B^8 in the solar-evolution process is prevented from taking place somehow or if the heavy-element abundance in the interior is a factor of ten or more below the observed surface abundance.

The predictions of current solar models (such as those by Zulema Abraham and Icko Iben Jr, MIT and Roger Ulrich and Bahcall, UCLA) are all about 9 ± 3 SNU, however, a factor of nine times greater than the Brookhaven upper limit. Recent work by M. Gari and A. H. Huffman at Cal Tech on the meson exchange correction to the proton–proton reaction reduces this

Jubilation at the Los Alamos Meson Physics Facility. LAMPF achieved its first proton beam at full design energy of 800 MeV on 9 June. Gathered at the computer control console are, in foreground from left, Harry Williams, Kenneth Crandall, Donald Swenson, Thomas Putnam, Robert Jameson and Louis Rosen (clapping hands).

In the initial operation the Los Alamos workers achieved approximately 0.1 microamp average current and 4 milliamp peak current. Rosen explained to us that such a high peak intensity indicates that they probably will not have trouble with beam blow-up. Still to be demonstrated is that they can avoid beam loss and achieve an average current of 1 milliamp on a regular basis (with a peak intensity of about 17 milliamp).

value to 7 ± 3 SNU.

There is another limit, of 0.3 SNU, which one would get if the sun shines only as a result of nuclear-fusion reactions in its interior and has no stellar evolution. The Brookhaven result does not disagree with this limit, but it strongly disagrees with the general wisdom. It is clear that something has to give.

The answer may lie in nuclear physics, in astrophysics or in neutrino physics. A. G. W. Cameron (Belfer Graduate School) points out that there is a tendency for workers in any one of these fields to feel that chances are slim that the fault lies in their own speciality; so one of the other fields must be involved, they believe.

A variety of explanations have been offered. Bahcall, Nicola Cabibbo and A. Yahill (Institute for Advanced Study) suggest that the reason you don't see any neutrinos is that they decay on their way from the sun, with a halflife less than 8 minutes for a 1-MeV neutrino (which is the energy to which the Brookhaven detectors are sensitive). Although he admits the hypothesis is "not pretty," Bahcall told us such a decay is not ruled out by terrestrial neutrino experiments, which deal with distances of the order of meters and with neutrinos of much higher energy than those coming from the sun. The hypothesis would require a finite mass for the neutrino. An experiment to test this hypothesis would be the reaction $Li^7 + \nu \rightarrow Be^7 + e$. This reaction is primarily sensitive to the very low-energy neutrinos from the so-called "pep" reaction, in which two protons and an electron go into a deuteron plus a neutrino.

Some theorists have suggested that the sun is changing its temperature on a cycle of 10^4–10^5 years. The solar radiation takes ten million years or so to diffuse up from the center to the surface and we observe the average energy produced during that time; so the cyclic variation would not be detectable. Unfortunately it is difficult to see why the sun would oscillate with such a period, since damping mechanisms are quite strong. However, since the sun is near convective instability transient mixing is possible with effects that will last for a period of the order of the Kelvin–Helmholtz time of approximately 10^7 years. William A. Fowler of Cal Tech has shown that the neutrino flux can be reduced to well below the observed limit for comparable periods, and this has been confirmed in detailed calculations by Robert Rood at Cal Tech and by F. W. W. Dilke and Z. O. Gough at the Institute of Theoretical Astronomy, Cambridge, UK.

Another suggestion, this time in nuclear physics, comes from Fowler. He says it is possible that there is a very narrow, excited state in Be^6, and it occurs where it would cut out the Be^7 and B^8 neutrinos by terminating the proton–proton chain at the $He^3 + He^3$ reaction. Current nuclear-physics ideas suggest such a narrow resonance is unlikely.

The Brookhaven experiment, done by Davis, John C. Evans, Veljko Radeka, Lee Rogers and John Galvin, is conducted a mile underground in the Homestake Gold Mine in Lead, South Dakota. The detector is a 100 000-gallon tank of perchlorethylene. Neutrinos are absorbed in Cl^{37}, forming Ar^{37}, which has a halflife of 35 days. The tank is exposed for two to three halflives (by the end of three months the production rate is equal to the decay rate) and then the Ar^{37} is removed by bubbling helium through the liquid. Helium is circulated through a cryogenically cooled charcoal trap to collect Ar^{37}. A small quantity of Ar^{36} is used as a carrier to make sure argon is recovered efficiently from the tank. The sample is then purified and placed in a very small gas proportional counter; one measures the 2.8-keV x rays coming from the decay of Ar^{37} back to Cl^{37}.

Besides measuring the energy of the decay, the Brookhaven group measures the rise time of the pulse, to distinguish between the Ar^{37} Auger electrons and pulses coming from various background processes. This added discrimination for Ar^{37} events lowers the counter background for Ar^{37}-like events, thus permitting more sensitivity to solar neutrinos.

An additional improvement to the experiment has been the addition of a water shield with an average thickness of about 2 meters; this eliminates the effect of fast neutrons from the surrounding rock. —GBL

Laser fusion

continued from page 17

Wood, Albert Theissen and George Zimmerman) is quite similar. Both groups talk about time-tailoring the laser pulse to maximize the implosion effect, but the details of tailoring differ. And both groups consider not only solid spherical pellets but also hollow spherical shells, a geometry that further reduces the required peak laser power and the complexity of the laser pulse form but requires about the same total laser pulse energy.

KMS Fusion is conducting classified research (without AEC funds) on the laser-implosion method, and it hopes to spend $50 million on the program in the next four years. The company has applied for patents on some of Brueckner's ideas, originated three years ago. (However these patent applications are being contested by AEC.) This is approximately the time when the AEC laboratories, Livermore and Los Alamos, began to rapidly expand their efforts in laser-produced fusion.

In a statement by Keeve M. Siegel, chairman of the board of KMS Industries, prepared for the Joint Committee, he said that if a significantly larger effort is mounted a "proof of principle" could be demonstrated in about three years; by this he said he meant that fusion energy output would exceed the energy input to the laser. AEC Commissioner Clarence E. Larson, commenting on Siegel's statement, said that AEC considers this time scale to be unlikely.

Brueckner, in his Ann Arbor lecture, notes that on the basis of intensive theoretical work, computing studies and limited experimental evidence, that strong nonclassical absorption occurs for laser intensities beyond 10^{11}–10^{12} watts/cm^2. Intensities appropriate to laser fusion are well above this threshold for the onset of anomalous absorption, and the result is that absorption efficiency approaches unity. Heating and penetration of energy from the laser deposition region leads, for a few kilovolts energy and solid density, to a pressure of 200 megabars. This huge pressure drives a strong shock into the unheated material ahead of the conduction wave.

For a spherical geometry, the temperature reached is a function of radius and shock pressure, Brueckner says, and can readily reach the required fusion temperature of 5–20 keV. He considers adjusting the rising pressure history so that successive shocks arrive at the center of convergence at the same time. For example, shocks driven by pressures of 1, 100 and 1000 megabars can each give a maximum compression ratio in spherical geometry of about 20; this leads to a net compression by a factor of 8000 or final density of 1600 gm/cm^3. The actual numerical studies carried out at KMS Fusion show that a more continuous pulse variation with time gives higher compression and efficiency than is produced by the discontinuous power increases, Brueckner told us.

By using a spherical shell of deuterium-tritium (equal amounts) of relatively large radius, the increased volume change on compression increases the hydrodynamic work caused by a given applied pressure, Brueckner notes; thus one can use less driving pressure for a given fuel mass. Brueckner concludes that it is easier to optimize the pressure and compression history for a shell than for a uniform sphere. He also remarks that the shell acceleration reduces the required laser power markedly.

Brueckner told us that with a laser-driven implosion the laser energy requirements for a laser-driven reactor are reduced by a factor of 10^7 from old laser-induced fusion calculations. These calculations gave approximately 10^{12} joules, assuming that the laser energy is multiplied by a factor of ten; this is required for overall energy gain.

The Livermore theorists describe their scheme as a spherical ablation implosion rocket. They note that the "scientific break-even" level at which laser pulse energy used equals the fusion energy produced is reduced from more than 10^9 joules for liquid-density deuterium–tritium to less than 10^3 joules in this new scheme. The scheme, they say, may reduce the laser energy required for commercial power production by more than a factor of 1000 from more than 10^8–10^9 joules with uncompressed pellets to 10^5–10^6 joules (assuming laser and thermal efficiencies of 10% and 40% respectively and 100% absorption of the laser light by the pellet). They consider an optimum laser pulse whose power rises faster than exponentially in time over tens of nanoseconds. The final portion of such a pulse delivers the second half of the laser pulse energy in a period less than a nanosecond, the final pulse duration depending upon the pellet mass and degree of hollowness. This pulse shape is equivalent to an optimum sequence of weak shocks of successively increasing pressure, which compresses the fuel nearly isentropically.

As a target they consider a droplet of liquid or solid equimolar deuterium–tritium, about 1 mm in diameter. By ablating about ¾ of the mass, they find it is possible to implode the remaining ¼ of the mass to about 10^4 times its liquid density—to 2000 gm/cm^3. The hydrodynamic history of the pellet is controlled via the shape of the laser pulse so that all the hydrodynamic characteristics intersect near the center, optimally compressing the pellet and igniting the pellet around its center.

The Livermore team states that their calculations differ from Brueckner's in several important respects. For example a pulse shape is used that implodes the pellet to a Fermi-degenerate state. This reduces the required laser energy by a factor of five to ten. Brueckner states however that his calculations in fact give results within 10 to 20% of the Livermore calculations. The independently developed numerical codes at Livermore and at KMS Fusion therefore give essentially identical results, he said. Carl Haussmann, who heads Livermore's laser effort, says that because the physical details of the two calculations differ, this result is surprising.

The Livermore workers noted that the use of spherical shells would sometimes be advantageous but they said that the thickness of such a fusion fuel bubble would need to be at least 2–3% of its radius because of implosion symmetry considerations and to effectively eliminate Taylor instability problems.

At the Lebedev Institute Basov, O. N. Krokhin and G. V. Slizkov have produced more than 10^6 neutrons from thermonuclear fusion with their nine-path laser. It consists of a successive parallel system of amplifiers. In the first stage a beam is split into three parts, each of which is then amplified by a rod. In the second stage each beams then converge from all direc- each is again amplified. The nine beams then converge from all directions onto a single target.

A still more powerful version is now being constructed, which will have 27 beams that will all be focused on a single target. It will yield 200 joules in 2 nanosec.

Livermore. The AEC's Division of Military Applications supports two very large efforts at Livermore and Los Alamos, both of which have undergone rapid expansion recently. Livermore's laser effort is asking for about $13 million in fiscal 1973 and had $8.5 million in FY 1972. From 1963 to 1970, the program, aimed at developing lasers for fusion microexplosions, spent $1 million per year. Haussmann told us that in the late 1960's this program was sharply accelerated because of the development of the ultrashort (less than 1 nanosec) mode-locked laser pulses required to initiate fusion microexplosions as well as the advent of high-energy, high-efficiency lasers (for example carbon dioxide) and hydrogen-fluoride chemical lasers.

At present Livermore has a neodymium-glass laser that produces 100 joules in 1-nanosec pulses; two 100-joule pulses can be produced two or three nanoseconds apart. Now they are building a multiple-path laser that will be a breadboard designed to help them learn how to build a 10^4-joule neodymium-glass laser, which they hope to start building in FY 1974. It would have four to sixteen separate beams symmetrically directed to a common focal point.

In typical Livermore experiments at present a 10–100-micron spot is focused onto a plane slab, say of deuterated polyethylene. From such a sample they have observed more than 10^4 neutrons/pulse. They also study the spectrum of x rays emitted, and use a spectrometer to observe the line structure of laser-produced plasmas of lead, gold and other elements.

Besides its efforts in target-design theory, Livermore's biggest emphasis is on understanding how to make energetic short-pulse lasers. Eventually Haussmann expects to see an increase in the pump efficiency of high-energy short-pulse lasers from its present value of 0.1% (glass) to perhaps 10% (for various gas media). At the same time these lasers must be able to deliver several orders of magnitude more energy than is currently possible. He also hopes to make the lasers reliable, eventually, so that you can push the

Omnidirectional laser-fusion device that was used by Ray Kidder and his collaborators at Livermore to study laser heating of deuterium ice pellets and other targets. This 12-beam device is essentially a scale model of the 10^4-joule laser proposed for FY 1974.

button and make them work every time, instead of just usually.

Los Alamos is asking for $6 million in FY 1973 and had $4.5 million for FY 1972 for its laser fusion effort, which started from zero early in 1969. Keith Boyer, who heads the program, told us that a basic change in thinking occurred at that time. Extremely short laser pulses became possible, and some experiments showed that the absorption was much stronger than one would expect from a simple-minded model. But the implosion idea has been referred to in unclassified literature as far back as 1963, he says. As the AAAS meeting, Nuckolls and Wood pointed out that the first detailed calculations on laser-induced implosion of thermonuclear fuel to high densities for controlled thermonuclear research purposes were conducted by Nuckolls at Livermore in 1961.

Hirsch told us of a paper by J. W. Diaber, Abraham Hertzberg and C. E. Wittliff, then of Cornell Aeronautical Laboratory, in *Physics of Fluids* **9**, 617, 1966, which describes laser-generated implosions. According to Brueckner, however, the analysis of Diaber and his collaborators did not discuss the laser energy deposition, transfer processes and thermonuclear energy generation; in addition their proposal would fail because of the reliance on single shock compression. Brueckner said that the AEC laboratories prior to late 1969 also appear to have discounted the possibility of achieving high compression and energy multiplication at relatively low laser energies.

Experiments are under way to measure temperature as a function of intensity, wavelength and pulse length. Although Los Alamos theoretical studies have included spheres and hollow shells, experiments have been limited to slabs.

The Los Alamos effort, aside from theoretical work, is directed mainly toward producing higher intensity lasers, which have rather special requirements, Boyer told us. One is that it is important to control the exact distribution of energy put into the target—unfortunately there can be intensity fluctuations across the focus spot by factors of ten. Another difficulty to be avoided is having laser energy dribble in for a long time before the main pulse, because a very high contrast ratio between the pulse and the background is what is actually needed. Finally the various lasers are all operating at much lower energies than are required. Typical energy estimates for laser implosion requirements range from 1000 joules to 1 megajoule, he said, depending on the precision with which requirements can be met and the exact details of the energy absorption and transport processes. The energy required for heating without compression was more like 10^9 joules.

A three- or four-path neodymium-glass laser is being constructed, which Boyer expects will produce 1 kilojoule in about 100 picosec; it is scheduled for completion in a year.

An electric-discharge-pumped gas laser is being built. By the end of 1972 they expect to get 1000 joules in 1 nanosec. In a couple of years it will be converted to a multiple-path system, which would yield 10 kilojoules. Even higher energies may be attainable by increasing the number of paths.

A long-term development program in chemical lasers is also under way. So far Los Alamos has obtained a few joules with a hydrogen-fluoride laser.

KMS Fusion expects to install in early autumn a 400-joule, 2-nanosecond neodymium-glass laser built by CGE and supplied by Hadron. A 1000-joule disc amplifier now under construction at General Electric will then be added to be driven by the Hadron laser. By early next spring they expect to raise the output to 2 kilojoules. Then experimenters will begin fusion tests aimed at a feasibility demonstration. Meanwhile they expect to do low-power experiments to verify the physics and predictions of the computer codes used for the design of the full-scale fusion experiments.

At the Naval Research Laboratory John Emmett directs a laser program that has recently gotten into the fusion game. In FY 1973 the total laser effort is expected to be about $3 million. In FY 1972 it was $2.5 million, about half of which is laser fusion.

NRL has a neodymium-glass laser that produces 215 joules in 200 picosec. Emmett says they have been concentrating on the couple of hundred picosecond range even though the lasers are harder to build, because "there's where the experiments are really going to be done." Efforts are now concentrated on pushing the output to 1000–2000 joules from a single aperture; that should be achieved about a year from now. Then one would go to the parallel-chain method to raise the energy as high as 20 or 30 kilojoules, which would take 10 or 20 parallel beams. He expects that such a large system would be built at one of the national laboratories because it would probably cost $30 million for 30 kilojoules.

Emmett's group expects to begin shortly investigating the laser-plasma interaction, using a variety of targets—microspheres, very fine fibers or very thin foils. They will try deuterated polyethylene, lithium deuteride and deuterium ice wire.

At the University of Rochester Moshe Lubin directs a program funded by a new (this year) consortium consisting of the university, General Electric and Standard Oil. The program is spending $1 million for FY 1972, whereas the previous two years it spent about $250 000. Lubin says he is concentrating on increasing the absorption, rather than on causing an implosion, because the dependence on absorption goes as the fourth power, whereas the dependence on compression goes like the square. This can be done through shorter-wavelength lasers and tailoring the laser pulse to the dense-plasma time history.

The Rochester group is building a neodymium-glass laser system that will fire one shot every two minutes. (NRL produces 1 shot every 8 minutes.) By January he expects it will produce 1 kilojoule, and at the end of two years, 5 kilojoules. The pulse duration is tunable between 10^{-11} sec and 10^{-9} sec.

Lubin and his collaborators are using spherical pellets, either of lithium deuteride or solid deuterium. Their laser is at 1.06 microns. Soon they expect to frequency-triple the radiation a number of times, by using large cells of gas. They have observed between 10^4 and 10^6 neutrons per pulse.

Elsewhere, at the Limeil Weapons Research Center F. Floux and his collaborators have observed 10^4 neutrons per pulse. They use four CGE VDC-640 lasers in parallel, hitting an extruded deuterium target from four directions. Their system produces 150 joules in 2 nanosec.

At Garching, Germany, workers have a subnanosecond glass laser system that delivers 10 joules. Using flat targets of deuterium they have observed thousands of neutrons. —GBL□