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LASER POSSIBILITIES IN PULSED CONTROLLED THERMONUCLEAR FUSION

James W. Shearer

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MASTER

LASER POSSIBILITIES IN PULSED CONTROLLED THERMONUCLEAR FUSION^{*†}

James W. Shearer
University of California
Lawrence Livermore Laboratory
Livermore, California

ABSTRACT

The possibility of extracting useful energy from deuterium has inspired serious plasma research for the last twenty years. The rise of laser technology during the last decade has led to some new proposals and perspectives on this problem.

It has been proposed to use a laser to heat a deuterium plasma in a uniform magnetic field similar to "conventional" fusion machine concepts. Large cryogenically cooled coils would be needed to provide fields of a hundred kilogauss or greater.

Another suggestion is that small thermonuclear "microexplosions" be created in a thick-walled vacuum chamber by means of a spherical array of laser beams focused on small spherical pellets of solid heavy hydrogen. These pellets must be prepared cryogenically and propelled into the vacuum chamber. This controlled fusion concept does not require a magnetic field for containment because the pellet plasma is so dense that sufficient nuclear reactions occur before it comes apart. The proposal involves questions of explosion magnitude and repetition rate, efficiencies of laser operation and light absorption, and energy recovery.

Much additional research is needed to evaluate the viability of these proposals and to compare them with other controlled fusion concepts.

* Work performed under the auspices of the U.S. Atomic Energy Commission.

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LASER POSSIBILITIES IN PULSED CONTROLLED THERMONUCLEAR FUSION[†]

James W. Shearer
University of California
Lawrence Livermore Laboratory
Livermore, California

1. The Controlled Fusion Problem:

The demand for energy and power continues to climb while our resources of coal and oil are beginning to dwindle.¹ This energy crisis has spurred the search for other sources of power; one such possibility is the energy release obtained from nuclear fusion reactions in the heavy isotopes of hydrogen -- deuterium and tritium.

The hydrogen bomb is the only way in which appreciable amounts of nuclear fusion energy have been released by man. For obvious reasons, this is an unsatisfactory source of continuous useful power. For over twenty years, research has been under way throughout the world, searching for an alternative method of releasing the energy of nuclear fusion in a manner that can be controlled on an industrial scale. Thus far the achievement of this goal has eluded all efforts.²

The expansion of laser technology in the last ten years now allows us to consider some additional possibilities for the controlled release of

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fusion energy. However, there are some formidable technical challenges in these new possibilities, and much remains to be learned. This paper is intended as a brief, introductory review of these concepts.

2. High Power Pulsed Laser Systems

Two different lasers dominate the high power pulse field today: the neodymium-glass laser, and the carbon dioxide laser. Some "typical" characteristics of the light output from the largest of these lasers are indicated in Table I. The near infrared neodymium glass laser³ consists of glass that is doped with 1% - 5% neodymium oxide. The Nd^{+3} lasing transition is excited by optical pumping from xenon-filled flashlamps. Its low efficiency arises from the fact that most of the flashlamp light is at the wrong wavelength for excitation of the excited level.

The far infrared carbon dioxide molecular laser has been built in many forms; the most promising for high pulsed power applications is the recently developed "TEA" laser⁴ (Transverse Electric Atmospheric). In this laser the excited molecular vibrational level is created by an electric discharge at atmospheric pressure whose electric field is transverse to the axis of the laser cavity. The optimum discharge is in the abnormal glow region, and considerable technical ingenuity is required to prevent arc breakdown and maintain optical homogeneity. One such design is pictured in Figure 1. Nevertheless, the TEA laser is undergoing rapid development at this time because its high efficiency and low cost offers the promise of many future applications.

TABLE I

"Typical" High Power Pulsed Laser Characteristics

<u>Laser</u>	<u>Ni-Glass</u>	<u>CO₂</u>
Wavelength (cm)	1.06×10^{-4}	10.6×10^{-4}
Cutoff Density (see Sec. 5)	10^{21}	10^{19}
Largest Output Energy (joules)	100-1000	100-1000
Pulse Length (nanoseconds)	.01 - 10	1 - 100
Efficiency	~ 0.1%	~ 10%
Cost	~ 10^3 \$/joule	~ 10-100 \$/joule

These are the most advanced high power lasers available today for research into the pure fusion problem.

3. Controlled Thermonuclear Reaction Conditions:

The lowest temperature self-sustained thermonuclear burn is the deuterium-tritium (DT) reaction (~ 100 million degrees in a 50:50 mixture of DT)

where the alpha particle (He^4) carries off an energy of 3.5 MeV per particle, and the neutron (n^1) has 14.1 MeV per particle. Additional energy (≈ 5 MeV) is released when the neutron is captured by surrounding material. The total energy release by all the reactions must exceed the energy necessary to raise the fuel to ignition temperature, in order for the excess energy to become available as useful power. This condition can be expressed mathematically by the "Lawson criterion" for the DT reaction;

$$n\tau > 5 \times 10^{13} \frac{e}{e} \text{ sec cm}^{-3} \quad (2)$$

where n is the ion density, τ is the confinement time of the plasma, e is the ratio of nuclear reaction energy output to laser energy input, and ϵ is the efficiency of absorption of laser light.⁵

An important practical limitation of "conventional" thermonuclear machines is the achievable containment P_c , whether that pressure be gas pressure or magnetic pressure contained by a coil. Choosing $P_c \leq 2000$ atmospheres, we then find an upper limit for the ion density n which can be contained at the ignition temperature T mentioned above:

$$n = \frac{1}{2} \frac{P}{kT} < 10^{17} \text{ cm}^{-3} \quad (3)$$

where we have assumed that the electron pressure equals the ion pressure. When we now compare equation (2) and (3), we obtain a condition on the confinement time τ :

$$\tau > 5 \times 10^{-4} \left(\frac{\alpha}{\epsilon} \right) \text{ sec} \quad (4)$$

An additional requirement of such fusion machines is thermal insulation of the plasma from the walls. Large magnetic fields are used to provide this insulation and to contain the plasma; the magnetic field which is required to contain 2,000 atmospheres pressure is ≈ 220 kilogauss.

It would take us too far afield to catalogue here the variety of proposed fusion machines and the problems of plasma instability that have plagued fusion research for so many years. Instead, we shall describe two laser/fusion proposals: first, a "conventional" fusion machine concept which might be improved by laser heating; second, a radically different fusion proposal involving laser-induced "micro-explosions" of solid DT pellets.

4. Laser Heating of Long Confined Plasma Column:

An important parameter for laser/plasma heating is the absorption coefficient of the laser light. The best known process for this is collisional absorption, whose mean free path l_c is, approximately:

$$l_c = \frac{10^{22} T^{3/2}}{Z^3 n^2 \lambda^2} \text{ cm} \quad (5)$$

where T is the temperature in degrees Kelvin, Z is the atomic number of the ion, and λ is the vacuum wavelength of the light in cm. Using the previous discussion we set $T = 10^8 \text{ K}$, $n \leq 10^{17}$, $Z = 1$, and $\lambda = 10.6 \text{ } \mu\text{m}$ (CO_2 laser light), and we find:

$$l_c = 10 \text{ km} \quad (6)$$

An even longer mean free path is found for neodymium light at the same density.

This large result might be reduced in two ways. First, at high laser light intensities other absorption processes involving plasma instabilities can be excited, which promise to lower the mean free path by several orders of magnitude.⁶ Second, one can hope that efficient longer wavelength lasers may be developed in the future, which would also lower l_c .

In Figures 2a and 2b we compare the "conventional" theta pinch fusion machine concept with a possible laser-heated plasma column machine, first

proposed three years ago.⁷ The expensive high energy low inductance capacitor bank that both heats the theta pinch plasma and provides the containment magnetic field is replaced by two items: an axial laser beam that heats the plasma, and a large magnetic field coil that surrounds both the plasma and the one meter liquid lithium blanket. In both machines the lithium is needed to capture the heat from the neutrons and to regenerate tritium (T) by means of the reaction:

The plasma column must be long enough so that end losses do not quench it. These losses can be roughly estimated from the deuterium plasma's sound velocity, which is approximately 10^8 cm/sec at $T = 5 \times 10^7$ °K. Then the length L is, approximately:

$$L > 2v_a \tau \approx .7 \frac{a}{c} \text{ Km} \quad (8)$$

This distance is comparable to the absorption mean free path (Eq. 6); it might be lowered with more complicated magnetic field shapes, to inhibit the axial flow.

The light beam must stay on axis, and not strike the walls over this long distance. Calculations have shown, however, that if the heated plasma column has a hollow density distribution, its refractive index profile forms a light pipe which channels the laser light down the axis.⁸

If the 10 km plasma column has a cross-sectional area of 0.1 cm^2 , then 50 megajoules of heat is required to reach 100 million degrees. This implies a very large laser, compared to current practice. The minimum required laser power, obtained by dividing this energy by the decay time, is of the order of 10 GW-a figure which is now being approached in practice at much shorter pulse lengths (100 nanoseconds) by TBA lasers.⁹

It can be seen that many formidable technical challenges are posed by this fusion machine concept, not the least of which is the cryogenic coil! It must be 2 meters in diameter, a few kilometers long, and produce a uniform 220 kilogauss field. Alternatively, if the coil were wound inside the lithium blanket, it could be smaller, but it would have to withstand intense heating from the neutron flux.

5. Laser-triggered Fusion Microexplosion Concept:

Figure 3 illustrates a radically different proposal for useful fusion energy release.^{10,11} A spherical array of laser beams is focused in vacuum on a solid spherical pellet of DT, which is then heated and compressed by the laser light until it ignites and burns in a "microexplosion" -- sufficiently small to be contained by the walls of the vacuum vessel. The lithium blanket serves the same purpose as in the previous proposal, but in this scheme no magnetic field is needed, as we shall see.

This proposal is actually more than ten years old, and it has an obscure, complicated, and controversial history. It has recently attracted much publicity because of a patent dispute and the revelation of previously classified computer calculations.¹²

In order to better understand the theoretical basis for this scheme, consider a sphere of DT whose ion density n is given by:

$$n \approx \eta n_0 \approx 5 \times 10^{22} \eta \quad (9)$$

where n_0 is the solid density and η is the "compression factor". If this sphere is at temperature T , the containment time τ can be written as:

$$\tau = \frac{1}{K} \frac{R}{V_s(T)} \quad (10)$$

where R is the radius and $V_s(T)$ is the velocity of sound. K is a normalization factor, which is about 4-5. Equation (10) is a mathematical expression of the principle of inertial containment -- that is, the reacting material will hold together for a time τ before the rarefaction wave "eats in" from the surface, and it flies apart. Inertial containment is being substituted for magnetic field containment in this proposal.

The next important question is: how large a "microexplosion" is contemplated? This can be calculated from the ignition energy E_i for the sphere:

$$E_i = \left(\frac{4}{3} \pi R^3 \right) \left(n_0 \eta \right) \left(\frac{3}{2} k (T_e + T_i) \right) \quad (11)$$

where k is Boltzmann's constant, and T_e and T_i are the electron and ion temperatures, respectively.

If we substitute numbers into this equation (choosing $T_e = T_i = 10^8 \text{K}$), and apply the Lawson criterion for containment (equa. 2), we can show that⁵

$$E_i = K^3 \alpha^3 / \epsilon^3 \eta^2 \quad \text{megajoules} \quad (12)$$

Since the laser energy E_L and the nuclear yield energy E_N are given by:

$$E_L = E_i / \epsilon \quad E_N = \alpha E_L \quad (13)$$

we can write that the "microexplosion" energy is:

$$E_N = 100 \alpha^4 / \epsilon^4 \eta^2 \quad \text{megajoules} \quad (14)$$

where we have put $K^3 = 100$. For comparison, 100 megajoules corresponds to the energy yield of ~ 50 pounds of high explosive, which may be difficult to control. Furthermore, there are no megajoule lasers in existence or immediately contemplated today. Thus, we would like to make the energy E_N as low as possible.

Now $\epsilon < 1$ by definition, and $\alpha > 1$ for practical application; therefore, the only way to reduce E_N is by increasing the compression factor η . This is the principle that is now emphasized by several groups; values of η up to as high as 10^4 have been calculated.¹²

How could laser light produce such a high compression? The calculations predict that it would be created by the high pressure (millions of atmospheres or more) produced at the surface of the pellet by laser heating. The outer surface ablates into the vacuum, crushing the inner material by "rocket reaction". However, a high degree of spherical symmetry would be required to obtain the highest compressions. Whether such high values as quoted above could ever be achieved in practice is not known.

The microexplosion energy (eq. 14) is an even more sensitive function of the light absorption efficiency ϵ at the surface of the solid DT pellet. The ablating material forms a density gradient which the light can penetrate only as far as the "cutoff density" N_c , where the light frequency equals the plasma frequency. (This is the same cutoff density that appears in the theory of radio waves in the ionosphere, translated to higher frequencies and densities.) The effective absorption is then the sum of the absorption over the light path in and out of the plasma. Table I shows that the cutoff density for available lasers is less than solid density, so all the light absorption will be in the outer ablation plume around the solid core. Thermal conduction carries the energy toward the center. All of these phenomena involve difficult plasma physics problems that are still under study; however, it appears at present that high absorption efficiencies would be much easier to obtain if a shorter wavelength, ultraviolet pulsed laser were available, whose light could penetrate closer to the core.¹³

Table II gives some examples of possible values of the parameters discussed above. Note that low values of microexplosion energy correspond to very short containment and heating times for the experiment (and for the laser pulse).

TABLE II: VARIOUS HYPOTHETICAL MICROEXPLOSIONS

Purpose	Energy Multiplication α	Light Absorption Efficiency ϵ	Compression Factor η	Pellet Radii		Containment Time τ (psec)	Laser Pulse Energy E_L (MJ)	Nuclear Output Energy E_N (MJ)
				Uncompressed R_0 (μm)	Compressed R (μm)			
Breakeven Experiment	1	1	1	5,000	5,000	1100	100	100
"	1	.5	1	10,000	10,000	2200	1600	1600
"	1	.5	10^2	464	100	22	.16	.16
"	1	.5	10^3	100	10	2.2	.0016	.0016
"	1	.25	10^3	200	20	4.4	.0256	.0256
"	1	.25	10^4	43.2	2	.44	.000256	.000256
Fusion Power	10	.5	10^2	4,640	1,000	220	160	1600
"	10	.5	10^3	1,000	100	22	1.6	16
"	10	.25	10^3	2,000	200	44	25.6	256
"	10	.25	10^4	432	20	4.4	.256	2.56
"	20	.25	10^4	864	40	8.8	2.05	41
"	40	.25	10^4	1,728	80	17.6	16.4	656

This proposal obviously poses a large number of formidable technical problems; one requirement of cryogenic interest is the DT pellet machine. It must be able to reproducibly manufacture spherical DT solid pellets of the order of $\sim 100 \mu\text{m}$ radius (barely visible specks). Then, like a baseball pitcher with exceptional control, the machine must propel each pellet into the center of a ~ 1 meter vacuum chamber so that it intersects with the laser focus to an accuracy of the order of $\sim 10 \mu\text{m}$. A typical pellet injection rate might be 10 pellets per second. In order to meet competitive energy prices, the individual cost per pellet must be a fraction of a cent.

Another technical challenge common to both laser-fusion proposals is the enormous vacuum pumping capabilities that are required to evacuate the spent fuel after each pulse.¹⁴ In a power-producing fusion reactor this will probably impose a requirement that the pumping time be only a fraction of a second.

Another problem, probably involving cryogenic techniques, is the recovery of unburned deuterium and tritium from these vacuum pumps in order to recycle this fuel back into the reactor.

6. Conclusions:

Whatever becomes of these imaginative proposals for laser-triggered fusion, it is obvious that they are not a short term panacea for the energy crisis. Optimists may differ, but in this author's opinion the only realistic assessment is that these are long shot possibilities for useful energy sources in the next century. On the other hand, they do represent the kind of imaginative thinking that may stimulate other ideas in the more immediate future.

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FIGURE CAPTIONS

- Figure 1 A view taken looking down the axis of the laser beam into a TEA CO₂ laser. The polished anode is above the beam axis, a "double discharge" type of cathode is below the beam axis.
- Figure 2 Two fusion machine concepts at a plasma density of $\sim 10^{17}$ ions/cc.
- (a) The fast discharge "theta pinch" concept; the Los Alamos "SCILLA" machine is an example.
 - (b) A laser heated plasma inside a magnetic field, as described in the text.
- Figure 3 Cutaway view of twenty-beam version of laser-triggered fusion microexplosion concept. Not shown is the DT pellet machine, the vacuum pumps or the laser optics.

Figure 2

Figure 3