Laser initiation of thermonuclear reaction in inhomogeneous spherical targets

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We consider physical processes in thermonuclear target for laser-induced thermonuclear fusion; these processes make it possible to obtain an energy gain $\sim 10^3$ at $E_{\text{las}} = 10^6$ J.

The optimization of the laser + thermonuclear target system based on the principle of spherical compression has stimulated the search for systems possessing large energy gains but imposing modest requirements on the parameters of the laser pulse and on the target-preparation technology. The physical principles of constructing a system with large energy gain are the following: the thermonuclear fuel must have a high average density in the final state; the density and temperature profiles resulting from the motion of the material to the center should satisfy the conditions for the initiation of the thermonuclear reaction in the central region and for subsequent propagation of the reaction zone to the periphery; the total thermal energy of the target material in the final stage should constitute an appreciable fraction of the laser radiation energy E_{las}.

In contrast to the ideas underlying the model with a special momentum profile and ultra-high compression ($\sim 10^3$ g/cm^3),[2] and the model where the compression of the fuel is effected by a heavy shell,[3–5] we propose that to obtain high gains ($E_{\text{ther}}/E_{\text{las}} > 10^2$) it is necessary to investigate the compression regimes of fuel masses much larger than in[2–4] to lower densities ($\sim 10^2$ g/cm^3).[1]

We propose in this paper a new laser pulse + target system, based on the use of a laser pulse of simple waveform and inhomogeneous shell targets with large thermonuclear-fuel mass, approximately 10^2 times the value in[2–4] As will be shown below, the new scheme yields a thermonuclear yield (gain) $E_{\text{ther}}/E_{\text{las}} \approx 10^3$.

The main idea of the proposed scheme is connected with the existence of a compression regime of hollow spherical shells with large ratio of radius to thickness, $R/\Delta R \sim 10^2$. Using such targets it is possible to compress masses $10^{-3} - 10^{-2}$ to densities $\sim 10^2$ g/cm^3, with a laser pulse of simple waveform at $E_{\text{las}} = 10^5 - 10^6$ J. When such a target is acted upon by a radiation pulse of duration much shorter than the time of collapse of the material to the center, the compression process occurs during a stage when the material is decelerated near the center. The average level of the entropy of the compressed matter is determined principally by the amplitudes of the first shock wave, and if the radiation flux reaches $10^{12} - 10^{14}$ W/cm^2, this level is low enough. Some effect on the compression of the bulk of the matter is exerted by the diffusion of the entropy from the central region of the target, which is heated as a result of the collapse.

The conditions formulated above make it possible to determine the dimension of the target and the duration of the pulse at a given laser energy. As shown by the estimates that follow, the characteristic scales at $E_{\text{las}} = 10^6$ J are $R_0 \sim 1$ cm, $\tau_{\text{las}} \sim 10^{-7}$ sec, fuel mass 10^{-2} g, density 10^2 g/cm^3, and $R_0/\Delta R_0 \sim 10^{-2}$. The fraction of the laser radiation energy converted into the energy of the compressed matter (the hydrodynamic efficiency) is $\sim 20\%$, thus ensuring, with appropriate profiles of the material parameters in the final state, a high efficiency of thermonuclear combustion.

We present next simple estimates that confirm the feasibility of the described scheme. The maximum compression of the material during the isentropic stage is determined by its entropy (or by the initial internal energy), and can be obtained from the relation

$$\delta = \frac{\rho}{\rho_0} \approx \left(\frac{E_0 + E_{\text{kin}}}{E_0} \right)^{\frac{1}{\gamma - 1}} \tag{1}$$

E_0 is the initial internal energy and $E_{\text{kin}} = mv_0^2/2$ is the kinetic energy.

If the target mass is concentrated in a thin spherical layer Δ, we obtain from (1)

$$\delta \approx \left(\frac{R_0}{\Delta} \right)^{\frac{1}{\gamma - 1}} = \left(\frac{R_0}{\Delta} \right)^{3/2}, \quad \gamma = \frac{5}{3}. \tag{2}$$

In practice it appears that the ratio R_0/Δ cannot exceed $\sim 10^2$, owing to the limitations connected with the symmetry of the compression, and this yields $\delta \approx 10^3$.

At the instant when maximum compression is reached, the kinetic energy goes over into thermal energy. As a result we have from the energy conservation law

$E_0 = 10^6$ J

DT mass g	R, cm	Pulse duration, sec	Transfer coefficient η, %	Density, g/cm³		Temperatures, keV		$\frac{E_{tn}}{E_0}$
				central	average	central	average	
10^{-3}	0.3	$1.5 \cdot 10^{-8}$	9	30	960	21	0.65	122
$2 \cdot 10^{-3}$	0.3	$1.5 \cdot 10^{-8}$	11	20	140	14	0.4	160 + 320
$1.5 \cdot 10^{-2}$	1	10^{-7}	20	1	100	6	0.04	10^3
			$E_0 = 10^5$ J					
$6 \cdot 10^{-5}$	0.1	$3 \cdot 10^{-9}$	8	46	1100	10	0.54	110
			$E_0 = 10^4$ J					
$6 \cdot 10^{-6}$	0.05	$2 \cdot 10^{-9}$	8.5	54	1160	18	0.55	80

$$\frac{m}{\gamma - 1} v_1^2 \cdot \delta^{\gamma - 1} = E_{las} \eta, \qquad (3)$$

where v_1^2 is a quantity characterizing the material entropy induced by the first shock wave. The hydrodynamic efficiency depends on the target radius and increases with increase of the latter ($\eta \to 41\%$ as $R \to \infty$). Numerical calculations show that $\eta \approx 15$—20% at $R \approx 1$ cm. The quantity v_1^2 is proportional to the amplitude of the first shock wave and cannot be less than the value 10^{11} cm²/sec² corresponding to the speed of sound in the solid. Assuming in (3) $\delta = 10^3$, $v_1^2 \approx 10^{11}$ cm²/sec², $\gamma = 5/3$, $E_{las} = 10^6$ J, and $\eta = 20\%$, we obtain the limiting value of the compressed mass

$$m \approx 3 \cdot 10^{-2} \text{ g}.$$

In the considered scheme, the conversion of the radiation energy into kinetic energy of the compressed material is determined by the structure of the target—the ablation layer is separated from the thermonuclear fuel by a layer of material with large Z and with mass on the order of the mass of the fuel. In contrast to[3–5], the layer of heavy material does not act as a compressing piston, but as a barrier that does not conduct heat. The problem of initiating the fuel can be solved by introducing additional internal layers, which lead to localization of the entropy in small masses of the thermonuclear material during the collapse process.

Of great importance for the realization of the proposed scheme is the question of the symmetry of the irradiation and the stability of the process of compression of shells with large values of the parameter $R/\Delta R$. Preliminary results (which will be reported in a separate article) show that the parameters of the target material during the course of compression, with allowance for the instability, are close to those obtained in the spherically symmetrical case under reasonable requirements imposed on the symmetry of the irradiation and the technology of target preparation.

The presented physical estimates were confirmed by numerical calculations of targets selected on the basis of the foregoing principles. We consider a hollow spherical target consisting of a successive set of shells—an ablation layer (CH$_2$, Be, etc.), a layer of heavy material (Pb, Au, etc.) with mass $\sim M_{DT}$, a layer or set of layers containing the thermonuclear fuel. We solved the system of equations of two-temperature hydrodynamics with allowance for the absorption of the laser radiation (including the anomalous absorption effects), the electronic thermal conductivity, the transport of α particles and neutrons, the ionization kinetics, and the losses to the intrinsic radiation.

We present below a table containing the characteristic results, time diagrams of the entropy at the center and on the periphery of the thermonuclear-fuel layer, and

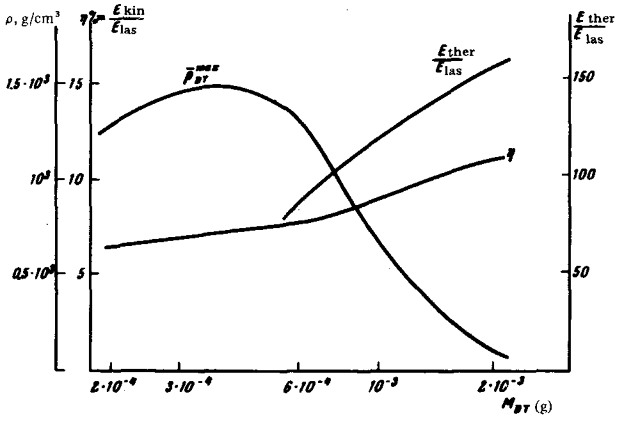

FIG. 1.

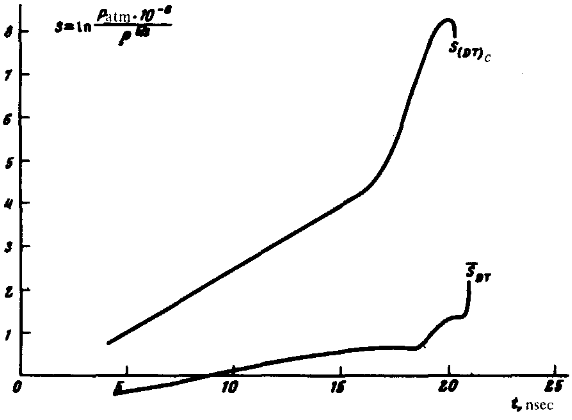

FIG. 2.

also plots of the average density, of the hydrodynamic efficiency, and of the thermonuclear yield against the fuel mass at a specified target radius.

Calculations in which the layer of heavy material was replaced by a layer of carbon with the same mass were performed for targets of this type. The final parameters of the thermonuclear fuel and the gain remained practically unchanged. We verified the sensitivity of the yield to the waveform of the laser pulse. A rising pulse with "sharpening" $q(\tau)/q(0)=64$ and a pulse of triangular form leads to practically the same gain.

Calculations were also performed for targets of this type with variation of the composition of the thermonuclear-fuel layer, in particular, the thermonuclear yield remains the same at the composition $D_{0.78}T_{0.22}$. This result points to a possibility of using in the future, targets containing predominantly deuterium.

Thus, the numerical experiments confirmed the feasibility of obtaining gains $\sim 10^3$, in contrast to the models of [2-5], in which the thermonuclear yield cannot exceed $\sim 10^2$ at $E_{las}=10^6$ J. We exphasize that in the experiments of[5] the DT gas is compressed with the aid of a heavy shell with mass much larger than the DT mass. A target similar to that of[5] leads in the case of $E_{las}=10^6$ J to a thermonuclear-fuel mass $M_{DT}\sim 10^{-4}$ g, and consequently to gains $E_{ther}/E_{las}\approx 10^2$.

The foregoing data show that the proposed scheme can be used to formulate a new approach to the development of a laser + target system for the purpose of obtaining a closed energy cycle in a laser thermonuclear reactor. The developed concepts may be useful for the development of other pulsed thermonuclear devices, for example for the initiation of a thermonuclear reaction by an electron beam.

It should be noted in conclusion that the gas dynamic calculations of the targets are based on the experience gained by high-temperature hydrodynamics research in the USSR.

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