density and velocity of the plasma for z = 1.1. The starting stages correspond to the appearance of self-focusing and the formation of a waveguide channel under the action of the field. The final stages of this picture, t = 2.9 and t = 3.1, correspond to the free motion of the plasma and collapse of the waveguide channel. The parameters in Fig. 5 are the same as in Figs. 3 and 4.

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SINGULAR SELF-SIMILAR SUPERDENSE COMPRESSION REGIMES FOR LASER TARGETS

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UDC 532.51+533.95

The approach to laser-driven fusion reactions proposed in [1, 2] is based on a special mode for depositing energy in the laser target that ensures compression of matter to densities of the order of 10^3–10^4 times the initial solid density. The optimum choice of laser pulse shape and target parameters on the basis of numerical calculations presents great difficulties. The key idea in the calculations is usually the requirement of adiabatic compression of the dense core of the target. Dimensional analysis then permits establishing the asymptotic law for the increase with time of the mechanical power expended on compression [3]: $E_m \sim |t|^{-2}$ (here and below, we consider spherical compression of matter with an adiabatic index $\gamma = 5/3$; time is measured from the instant of collapse). A particular self-similar solution, satisfying this law, is indicated in [4, 5]. In this case, the following questions remain unclear: 1) Does the self-similar correspond to the only optimum compression regime and are flows close to self-similar flows realized with the numerical simulation? 2) How is the laser pulse shape related to the time dependence of the mechanical power? In the present work, it is shown that the solution in [4, 5] is not the only solution in the sense indicated and two new families of self-similar solutions are constructed to the equations of gasdynamics, describing the compression of simple shell-like and continuous uniform laser targets. The solutions constructed are singular; the corresponding values of the self-similar indicators lie within some interval of acceptable values. In order to construct the solutions, it is necessary to transform to a scale-invariant representation of the hydrodynamic variables. The reverse procedure for calculating the physical quantities requires the characteristic parameters of the medium: the specific entropy in the case of shells and the initial plasma density in the case of continuous targets. The solutions constructed describe the process of an unbounded concentration of energy as the instant of collapse is approached; in an actual experiment, the magnitude of the total energy, of course, is limited and determines the maximum degree of compression. It is shown by way of comparison with numerical calculations that for a correct choice of parameters the self-similar solutions found give a quantitative description of the dynamics of the compression of the dense core of a target in regimes that are similar to those studied numerically [1, 2]. It has been found that for shells with degrees of compression of practical interest, the law that describes the change in power can differ noticeably from the asymptotic law.

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We note that the solutions examined are useful for describing nonisentropic compression regimes, for which a converging shock wave (SW) appears as the initial perturbation. This is significant, since in experiments it is not possible to avoid the formation of an initial SW and the corresponding heating of the center of the target.

Analysis of numerical calculations [6] shows that in the case of thin shells the laser and mechanical power have a greatly differing time dependence. This difference is almost entirely related to the ablation of material, which leads to a decrease in the mass of the dense core.

As is well known, there are two regions with sharply differing properties in laser targets: the hot corona, in which light is absorbed and in which the reactive pulse is formed, and the dense core, which is compressed under the action of the reactive pulse. In the core, the heat flux is negligibly small, while the electronic and ionic temperatures are equal. For this reason, the compression of the core can be described by the system of gasdynamic equations. The latter have a class of particular solutions that depend on the variable $\xi = ar/(-t)^{\delta}$. The singular solutions that describe the cumulation of the entire mass of substance in the center of symmetry at some moment in time t = 0 are of interest for the problem of superdense compression.

Let us first examine the collapse of a shell. After a laser pulse with initial power $\dot{E}_0$ is turned on, an SW, which transmits to the substance a specific entropy $\Delta S = c_V \ln\mu$, $\mu \simeq 0.02\rho_0^{1/3}\dot{E}_0^{2/3}p_0^{-1}R_0^{-4/3}$ (ρ_0 is the initial density), arises in the shell. For thin shells, the entropy is uniformly distributed throughout the mass. Further compression occurs with constant entropy, and the finite degree of compression depends on the magnitude of the entropy. The system of equations of gasdynamics reduces in the usual way [7] to a single ordinary differential equation, in which the variables are the dimensionless flow speed and the speed of sound, which are related to the corresponding dimensional quantities by the relations $v(r, t) = (r\delta/t)\varphi(\xi)$ and $c(r, t) = -(r\delta/t)\psi(\xi)$. The singular solution sought corresponds to an integral curve in the plane (φ, ψ), connecting the singular point $Q(1, 0)$, which corresponds to the boundary with the vacuum, and the singular point $R(1/2\delta, 1/2\sqrt{3}\delta)$. Indeed, for the simplest singular solution $v = r/2t$, and $c = -r/2\sqrt{3}t$, the power law is given by $\dot{E}_m = 4\pi R_n^2 p_n v_n \sim |t|^{-2}$ (the subscript n denotes parameters of some fixed Lagrangian particle belonging to the dense core). For singular regimes with the asympmtotic law $\dot{E}_m \sim |t|^{-2}$ for $t \to 0$, it is necessary that $\varphi(\xi_n(t)) \to 1/2\delta$ and $\psi(\xi_n(t)) \to 1/2\sqrt{3}\delta$. Such integral curves exist under the condition that the index of self-similarity δ satisfies the inequalities $1/2 \leqslant \delta \leqslant (\sqrt{3} + 1)/2\sqrt{3} \simeq 0.7887$. For $\delta = 0.5$, the solution sought is given by the straight segment $\varphi = 1$ and the temperature distribution follows from the formula $\psi^2 = (\xi^2 - 1)/3\xi^2$, while the velocity distribution is linear with respect to the radius. This particular solution is studied in [4]. For $\delta < 0.5$, the integral curve lies entirely in the region $\varphi > 1$. In this case, the required asymptotic behavior is not satisfied for $t \to 0$. For $\delta > 0.7887$, the integral curve intersects the straight line corresponding to the doubling of the solutions S, the equation of which is $\psi = 1 - \varphi$ (for a more detailed discussion of the straight line S see [7]). Indeed, the curve leaves the saddle point Q along the separatrix $\varphi = 1 - \frac{9}{5}\frac{2\delta - 1}{1 - \delta}\psi^2 + O(\psi^3)$, but in this case $(2\sqrt{3}\delta)^{-1} < 1 - (2\delta)^{-1}$. Finally, if $\delta < 0.7887$, we have $(2\sqrt{3}\delta)^{-1} > 1 - (2\delta)^{-1}$. Here, the point R is a node. It can be shown that among the bundle of curves emanating from R, there is always one that hits Q.

Numerical integration is necessary in order to find the integral curve sought. However, there exists a sufficiently accurate approximate solution, which gives the following density profile:

$$\rho(r, t) \simeq \begin{cases} 0.25\left(-\dfrac{r}{\sqrt{\mu}\, t}\right)^3 [\delta(1 - \delta)\ln \xi]^{3/2}, & \xi < 1.4, \\ 0.011\left(-\dfrac{r}{\sqrt{\mu}\, t}\right)^3, & \xi > 2, \end{cases}$$

where $\xi = r/r_0(t)$; $r_0(t)$ is the internal radius of the shell. The accuracy of the formulas is not lower than 10%. Figure 1 shows the trajectory of a Lagrangian particle with 0.18 M_0 and the change in the density in the particle as a function of time; and, the self-similar

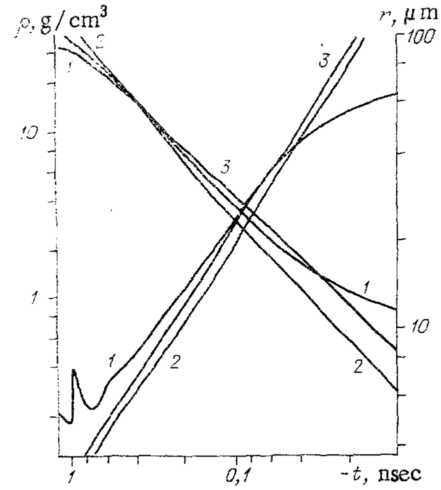

Fig. 1

solution sought (curves 2, 3, $\delta = 0.77$ and 0.53, respectively) is compared with the numerical calculation (curve 1) of the compression of a shell, carried out for a simultaneous two-temperature hydrodynamic model taking into account absorption of light and transport processes with restrictions as to the flux [6] (the target consists of a DT mixture, $M_0 = 0.2$ μg, the thickness equals 10 μm, $\dot{E}_0 = 3\cdot10^9$ W). The calculation was performed for a laser pulse with shape given by $\dot{E}_l(t) - \dot{E}_0(t_0/|t|)^m$ with the parameters $t_0 = 1.2$ nsec, $m = 1.3$, and energy equal to 200 J. It can be seen that the motion of the dense part of the target is well described by the self-similar solution.

We note that for degrees of compression of practical interest $\sim10^3$–10^4, the motion of the shell still differs significantly from the asymptotic motion, corresponding to infinite compression, while the power expended on compression does not have a power-law dependence as a function of time. If the power is approximated as usual with a power-law approximation, then the exponent is always less than the asymptotic value. The magnitude of the exponent depends, of course, on the parameters of the shell and the degree of compression, so that the approximate expression presented above for the laser power is not a universal expression.

Let us now examine the singular regime for the compression of solid targets. The assumption of self-similar motion again allows reducing the problem to integration of a single ordinary differential equation [7, 8]. The integral curve sought connects the singular point $M(3/4, \sqrt{5}/4)$, corresponding to a strong shockwave, to the singular point $\left(1/2\delta, \sqrt{\frac{5}{3}\frac{2\delta-1}{4\delta+1}}\Big/2\delta\right)$. Approaching the latter point corresponds to reading the asymptotic region $\dot{E}_m \sim |t|^{-2}$. The physically correct solution exists for all values of δ satisfying the inequalities $1/2 \leqslant \delta < A(\gamma)$. The upper edge of the spectrum is determined from the condition that the points M and N lie on the same side of the doubling line S; in this case N is a node. We note that $A(\gamma) \leqslant \delta_g(\gamma)$, where $\delta_g(\gamma)$ is an index that corresponds to the converging Landau–Guderleya shock wave [8, 9], $A(5/3) = \delta_g(5/3) = 0.688$. For $\delta < 1/2$, the point N moves out of the physical region $p > 0$, $\psi > 0$. We note also (this remark also relates to the case of a shell-like target) that the edges of the continuous spectrum δ found above in principle can also include discrete values of the index δ, which give correct solutions to the problem and which correspond to integral curves that intersect S at the singular point. This question requires special analysis.

The solution is constructed as follows. Let a SW converge at the center of a target so that behind the SW front the temperature is given by $T \simeq 0.1\frac{M_i}{k}\left(\frac{\delta R_0}{t_0}\right)^2\left(\frac{|t|}{t_0}\right)^{2(\delta-1)}$, where M_i is the ionic mass, k is the Boltzmann constant, R_0 is the initial radius of the target, and t_0 is the duration of the pulse. The spatial profiles of the density and temperature in the solid target are shown in Fig. 2 ($1 - \delta = 0.527$, $2 - \delta = 0.667$). In the shock wave regime, the temperature in the perturbed region depends weakly on the coordinates. Figure 3 shows a comparison of the average temperature of the compressed matter, computed numerically (curve 1), with the temperature behind the front of the self-similar shock wave for $\delta = 0.527$ and 0.667 (curves 2 and 3, respectively). The results correspond to a solid target, $M_0 = 0.2$ μg, $R_0 = 66$ μm, $t_0 = 0.87$ nsec, $m = 2$, and $E = 200$ J. The results show good agreement.

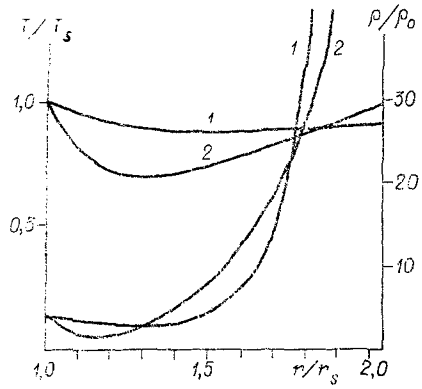

Fig. 2

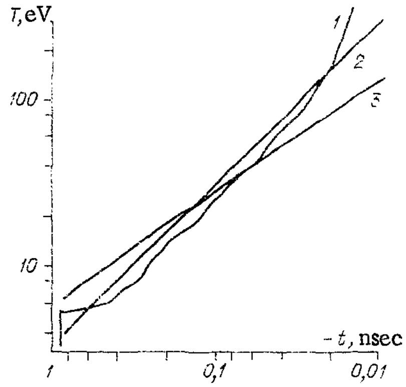

Fig. 3

Thus, the described self-similar solutions give the correct quantitative description of compression and heating of the dense regions of laser targets and can be used for optimizing laser plasma compression regimes and estimating the conditions for igniting thermonuclear laser-driven reactions.

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