Laser thermonuclear fusion with force confinement of hot plasma

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The possibility of the utilization of laser radiation for plasma heating up to thermonuclear temperatures with its simultaneous confinement by ponderomotive force is investigated. The plasma is located inside a powerful laser beam with a tubelike section or inside a cavity of duct section, formed by several intersecting beams focused by cylindrical lenses. The impact of various physical processes upon plasma confinement is studied and the criteria of plasma confinement and maintaining of plasma temperature are derived. Plasma and laser beam stability is considered. Estimates of laser radiation energy necessary for thermonuclear fusion are presented.

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INTRODUCTION

There are actually two marked out ways for the solution of the controlled thermonuclear fusion problem. These are the force technique, when hot plasma is confined (by means of magnetic field) during the time necessary for the reaction, and the inertial one, when thermonuclear reactions take the time, determined by hydrodynamic expansion.

Major restrictions in the case of force confinement are various hydrodynamic instabilities of plasma (see, for example, Ref. [1]), and in order to realize the scheme of inertial confinement, energy supply to the target should be considerably increased (in comparison with the one attained by now). Therefore, the urgent problem deals with the search of schemes where plasma would be sufficiently stable and the energies necessary for the controlled thermonuclear fusion would be feasible in the modern level of laser technique.

We believe that the solution to this problem can be found out by the utilization of the scheme suggested in this paper, where thermonuclear plasma is simultaneously heated and confined by laser radiation. In principle, one can imagine two possible variants of such a scheme.

In the first variant the confined plasma represents an elongated axially symmetric formation, with the confining ponderomotive force preventing it from

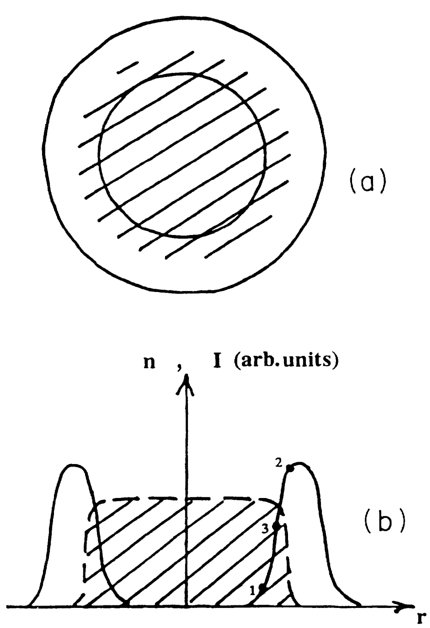

FIG. 1. Section (a) and the intensity profile (b) of a tubelike beam together with the area, occupied by plasma (hatched).

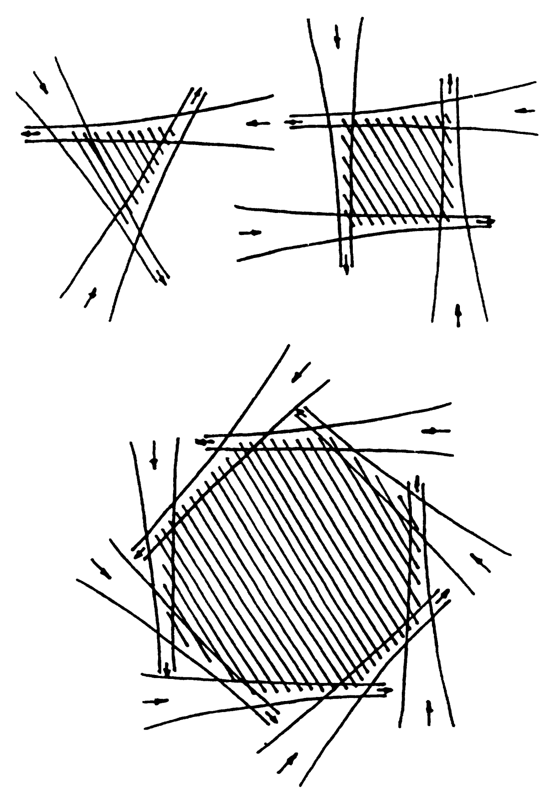

FIG. 2. Diagrams of the intersection of cylindrically focused beams. (Sections. The areas occupied by plasma are hatched.)

transversal spread and acting in a tubelike laser beam (or in two such beams, propagating in opposite directions) (Fig. 1). In the longitudinal direction the confinement can be realized either by the ponderomotive force of two additional laser beams propagating perpendicularly to the main ones and closing the area from the ends or (for the area that is not closed from the ends) by inertia and viscosity of plasma. In the second variant the confined plasma is localized inside a cavity of duct section, formed by the intersection of several beams focused by cylindrical lenses (Fig. 2).

The density of generated plasma should be high enough for the increase of radiation absorption and for the satisfaction of the Lawson criterion. At the same time the density of plasma electron's should be less than the critical density; otherwise, laser radiation will simply be unable to penetrate plasma.

CONFINEMENT AND HEATING: MAIN EQUATIONS

The correct introduction of a ponderomotive force into hydrodynamics equations is performed in the literature for the case of electrostriction self-focusing caused by plasma displacement out of the laser beam [2]. In the analysis conducted further we shall take into account only plasma motion under the effect of ponderomotive force, assuming that other hydrodynamic processes develop much slower. In this case the equations of plasma hydrodynamics can be written out as

$$\frac{\partial n}{\partial t}+\nabla\cdot(n\mathbf{v})=0 , \quad (1)$$

$$Mn\left[\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\nabla)\cdot\mathbf{v}\right]=-\nabla p-(n_e/2n_{\rm cr})\nabla E^2(r) . \quad (2)$$

Here E is the electric-field amplitude, n is the density of heavy particles, n_e is the electron density, M is the mass of ions, $\mathbf{v}$ is the hydrodynamic (macroscopic) velocity, $n_{\rm cr}=m\omega^2/4\pi e^2$ is the critical electron concentration, p is pressure, m is the mass of electron, e is the electron's charge, and ω is the angular frequency of laser radiation.

For hydrogen plasma $n=n_e$, and the condition of transversal equilibrium, considering plasma as an ideal gas is of the form

$$2nT=nE^2/2n_{\rm cr} , \quad (3)$$

the temperature T is measured in energy units. The condition of plasma confinement with the temperature T_f necessary for the controlled thermonuclear fusion can be written out as

$$E\geq E_{\rm th}=(4n_{\rm cr}T_f)^{1/2} \quad (4a)$$

for the field, or

$$I\geq I_{\rm th}=cn_{\rm cr}T_f/2\pi \quad (4b)$$

for the radiation intensity (c is the light velocity).

Thus the plasma is confined by the radiation if the radiation intensity exceeds the threshold value $I_{\rm th}$. The maximum value of the plasma being confined along the direction of the laser beam propagation $L_{\rm conf}$ will depend on the condition of the equality between the beam intensity (which decreases with its propagation) and the threshold intensity. This length must coincide with the length of the plasma, confined by the tubelike beam (or with the half-width of the plasma, confined by two tubelike beams running in opposite directions), or with the length of one facet along the direction of the beam propagation in the case of the duct cavity.

The radiation propagation in the problem under consideration is determined by three factors: diffraction, refraction, and absorption of the radiation. In order to simplify the problem we will not consider the diffraction at the side of the beam, external with respect to the plasma (i.e., we will consider the beam as nonlimited from this side). The influence of these processes on the character of the beam propagation is different. On the one hand, the beam diffraction at its internal boundary with plasma leads to the deviation of a part of the radiation inside the plasma. The absorption of the radiation in plasma results in the increase of the gradient of the beam intensity and, consequently, in additional diffraction of the radiation into the plasma. On the other hand, due to a considerable gradient of the plasma density the gradient of the refraction index is large and it determines the deflection of radiation out of the plasma (the beam refraction). The three physical processes mentioned are decisive in the problem under consideration. The influence of other processes, including the self-focusing filamentational instability of the beam, will be considered independently.

If the strongest of the considered mechanisms is diffraction, the field amplitude depends on the diffraction divergence of the beam, and the value of $L_{\rm conf}$ will be equal (with a certain coefficient) to the diffraction length of the initial beam. If the refraction prevails, the beam will be removed from the plasma, the plasma will "overtake" it, the beam will deviate still more, and finally the confinement will disappear at some distance. This distance can be called "refraction length"; in this case it will just be equal (also with a certain coefficient) to $L_{\rm conf}$. The refraction length has the same order of magnitude and the same physical meaning as the radius of the beam curvature in geometrical optics.

As the diffraction and refraction affect the laser beam in a directly opposite way, it seems to be quite important to study the possibility of their mutual compensation. It is obvious that if the refraction, on the one hand, and the diffraction (and absorption), on the other, are in a certain balance, then the beam will lose rather quickly its initial transverse distribution and, later on, propagate along the boundary with the plasma with the transverse profile, which is determined by the combined action of the three effects mentioned. Thus, one can state the problem as physically self-similar. In the case of appropriate balance $L_{\rm conf}$ can exceed all the three characteristic lengths, conditioned by the diffraction at the internal boundary between the beam and the plasma, by refraction and absorption. In this case $L_{\rm conf}$ is limited by the diffraction length, determined by the gradient of the radiation at the external boundary of the beam (this boundary can be rather considerable). It should also be noted that in this case the absorption length can be less than L_{conf}, since, due to diffraction, the plasma absorbs "new" radiation, which heats and confines it.

The considerations cited above are valid both for the beams of tubelike section and plane beams, resulting from the focusing of the radiation by cylindrical lenses and used for obtaining duct cavities. To substantiate the existence of the self-similar solutions in the case of plane beams we will consider the two-dimensional stationary problem on the confinement of a semi-infinite plasma by a semi-infinite beam. Let the plasma occupy first the semispace $x<0$, let the field be the semispace $x>0$, and let the radiation propagate along the z axis.

The equation describing the force balance in the plane, perpendicular to the z axis, is

$$\frac{\partial p}{\partial x}=\frac{n}{2n_{\text{cr}}}\frac{\partial E^2}{\partial x} . \tag{5}$$

We will assume that the plasma is isothermal, with temperature T_f, therefore the equation of state (it was already used above) is

$$p=2nT_f . \tag{6}$$

From the wave equation we will separate the stationary amplitude of the field $E(x,z)$ in the form

$$A=E(x,z)\exp(-i\omega t+ik_0 z) ,$$

where A is the electric field and k_0 is the wave number of the laser radiation in vacuum. Representing the real and imaginary sides of the dielectric penetrability through the plasma density, using Eqs. (5) and (6), we obtain the parabolic equation, describing the propagation of the radiation:

$$2ik_0\frac{\partial E}{\partial z}+\frac{\partial^2 E}{\partial x^2}-\frac{k_0 n_0}{n_{\text{cr}}}E\left[1-\exp\left[-\frac{E^2}{E_{\text{th}}^2}\right]\right]+2ik_0\delta_0 E\exp\left[-\frac{2E^2}{E_{\text{th}}^2}\right]=0 . \tag{7}$$

Here n_0 and δ_0 are the unperturbed (by field) plasma density and absorption coefficient of laser radiation in plasma. If $E \gg E_{\text{th}}$, both exponents tend to zero. The remaining equation describes the linear refraction, and if $n_0 \ll n_{\text{cr}}$ there appears a simple equation of free radiation propagation.

Three regions of E values are physically marked: $E \gg E_{\text{th}}$, $E \geq E_{\text{th}}$, and $E<E_{\text{th}}$. There is a confinement in the first region and none in the third one according to (4). The interesting region of E is the second. Let us expand into Taylor series $\exp(-E^2/E_{\text{th}}^2) \simeq (2-E^2/E_{\text{th}}^2)/e$ (e is a base of natural logarithm). This expansion is valid under $E^2-E_{\text{th}}^2 \ll E_{\text{th}}^2$ and slightly rough is the physics under $E \geq E_{\text{th}}$. Let us do the substitutions and introduce notations:

$$a=\exp(-ic_0\eta)(2/3)^{1/2}E/E_{\text{th}} ,$$

$$\xi=[6\delta_0 k_0/e^2]^{1/2}x ,$$

$$\eta=-3\delta_0 z/e^2 ,$$

$$c_0=e^2(1-2/e)k_0 n_0/6\delta_0 n_{\text{cr}} ,$$

$$c_1=-1, \quad c_2=-ek_0 n_0/4\delta_0 n_{\text{cr}} .$$

Equation (7) is reduced to

$$\frac{\partial a}{\partial \eta}=a+ic_1\frac{\partial^2 a}{\partial \xi^2}-(1+ic_2)a^3 . \tag{8}$$

The relation (8) is the Kuramoto-Tsuzuki equation [3]. It was shown [4] that it has self-similar solutions:

$$a=R(\xi)\exp[i\Omega\eta+ib(\xi)] .$$

It is the desired physical solution of the problem under consideration. We have the system of ordinary differential equations for R and b (variable ξ):

$$\Omega=-\frac{R''}{R}+b'^2-c_2R^2 ,$$

$$R^2=1+\frac{2R'b'}{R}+b'' \tag{9}$$

(the prime means the derivative with respect to ξ). The field under $\xi\to-\infty$ is absent, the amplitude and phase of it coincide with unperturbed ones under $\xi\to\infty$, and the phase $\to\pi/2$ under $\xi\to-\infty$ (total internal reflection):

$$R|_{\xi\to\infty}=0, \quad R|_{\xi\to-\infty}=R_0 ,$$

$$b|_{\xi\to\infty}=0, \quad b|_{\xi\to-\infty}=\pi/2 .$$

Here the value R_0 has to provide the confinement, i.e., exceeds $(\frac{2}{3})^{1/2}$. The system (9) is not solved analytically; the numerical solution of it is not more simple than the solution of the original Eq. (8) [and (7) too]. The solution of (9) will give the exact profiles of confined plasma depending on the geometry of the experiments—the shape of laser beam(s). It is clear that this formulation of a problem expands the frames of this paper, because the aim of it is to demonstrate the possibility and advantages of new methods of plasma confinement for fusion. For the first step, it is enough to determine Ω (and L_{conf}) through the physical parameters. If we obtain that the L_{conf} under such parameters will be large enough, we will receive sufficient confinement conditions [the necessary ones are (4)].

The sufficient confinement condition for the system (9) is clear: $\Omega=c_0$ or $L_{\text{conf}}=\infty$. Let us substitute the second equation of (9) into the first and estimate the value Ω. In the transversal section of the region of confinement (near point 2 on Fig. 1), $\partial/\partial x \simeq 1/r_1$ (r_1 is the transversal scale of the field amplitude droop into the plasma), $R'' \simeq b''=0$; it is easy to show that $R'>0$ but $b'<0$,

$$-b' \simeq (b_{\max}-b_{\min})/(2\delta_0 k_0)^{1/2}r_1$$

$$=\beta/(2\delta_0 k_0)^{1/2}r_1 ,$$

$$R/R' \simeq (2\delta_0 k_0)^{1/2}r_1 .$$

Boundary conditions give $\beta \simeq \pi/2$ and

$$\frac{1}{L_{\text{conf}}}=\frac{\beta^2}{2k_0r_1^2}-\left[\frac{7}{e}-2\right]\frac{k_0 n_0}{n_{\text{cr}}}+\frac{n_0\beta e}{n_{\text{cr}}\delta_0 r_1^2} . \tag{10}$$

The value $\beta^2/\{(7/e-2)k_0r_1^2\}\simeq L_d^{-1}$; here L_d is the length of diffraction of the internal edge of the beam; $e/\beta\delta_0\simeq L_a$, the absorption length; and $2n_{cr}/k_0n_0$ as was noted, can be interpreted as the refraction length L_r. The condition $\Omega=c_0$ will be fulfilled if

$$L_r=L_a-L_d \; . \tag{11}$$

Thus the confinement is possible along the length $L_{conf}\gg L_r$ even in case $L_d,L_a\gg L_r$. As we noted above, L_{conf} is really limited in this case by the diffraction of the external edge of the beam.

The equation describing the energy balance of the plasma volume unit can be written out as

$$dU/dt=-\kappa\nabla^2T-q^-+q^+ \; , \tag{12}$$

where U is the internal energy of plasma, κ is the electron thermal conductivity divided by the Boltzmann constant, q^+ is the rate of plasma volume unit heating, q^- is the rate of the heat losses from a volume unit of the plasma.

The energy to be spent on heating of the plasma column evolves in the laser beam area occupied by plasma and heats the main plasma volume due to electron heat conductivity. The complete balance of energy in the plasma can be obtained by integrating the expression (12) over the whole volume of plasma. It results in the losses of plasma energy on radiation and in the absorption of laser radiation in the area where the plasma intersects the laser beam. In fact, the heat flow from the "walls" of the beam into the plasma has the characteristic propagation time $\tau_{tr}\sim(\chi/r_0^2)^{-1}$, where χ is the electron thermal diffusivity and r_0 is the radius of the plasma column. Since $r_0<1$ cm, $\tau_{tr}<10^{-9}$ s, the time needed to obtain temperature stabilization over the plasma volume, is substantially less than the laser pulse duration. The heating of the plasma internal layers can also be realized due to a shock wave, generated by a pressure jump at the beginning of the laser pulse. In this case the heating time is $\tau_{tr}\sim D/r_0\sim v_i/r_0$ (D is the velocity of the sock wave; v_i is the thermal velocity of ions). Consequently, after the heating, the plasma temperature is determined only by the balance between the heating and the radiation losses. The main mechanism of heating is provided by the bremsstrahlung absorption, the absorption factor δ being defined by the expression

$$\delta=2\times10^{-28}n_e^2Z\lambda^2(1-n/n_{cr})^{1/2}/T^{3/2} \; ,$$

where T is measured in eV, Z is the value of ion charge in plasma, and λ is the laser radiation wavelength.

The heating rate of the whole plasma volume Q^+ is defined then by the formula

$$Q^+=2\delta\gamma NP/S_1 \; , \tag{13a}$$

where $N=(1-n/n_{cr})^{1/2}$ is the plasma refractive index, P is the total power of the laser pulse, $\gamma\simeq S_1/3S_p$, S_l is the cross-section square of the laser beam, and S_p is the cross-section square of the plasma column. It has been assumed for estimation (see Fig. 1) that plasma occupies $\simeq\frac{1}{3}$ of the laser beam cross section.

Only the bremsstrahlung is possible in a pure hydrogen plasma. Under stationary conditions the rate of losses for the whole plasma volume Q^- determined by this mechanism of losses must satisfy the condition $Q^-=Q^+$. It follows from this condition that the plasma temperature $T\sim\gamma^{1/2}$ and $T\simeq1$ MeV for $\gamma\simeq1$; therefore, in order to achieve the equilibrium at the temperature of 10 keV, γ must be $\sim10^{-4}$. Thus, pure deuterium-tritium plasma can be overheated by the field, since the amplitude of the field providing the confinement of the plasma is notably higher than the amplitude of the field necessary to attain the reaction temperature. The overheated plasma is not already confinable by the ponderomotive force.

It should be noted that the energy balance can be obtained easier in a nonhydrogen plasma. Therefore, the developd method can be considered for the reactions of nonhydrogen thermonuclear fusion, the cross section of which is sufficiently high [5]. The Lawson criterion is more strict in this case naturally; moreover, the confining field is approximately one order of magnitude greater. Consequently, the required laser energy must be 2–3 orders of magnitude higher than for the deuterium-tritium reaction. It does not mean however that nonhydrogen thermonuclear fusion is impossible under such an experimental approach.

To provide the balance of losses in the case of the D-T reaction, one should create an additional mechanism of heat removal. This can be achieved by (a) the existence of a cold substance in the center of the plasma collecting heat due to electron heat conductivity and (b) adding a small amount of heavy admixture, e.g., a noble gas or the vapors of a heavy metal, providing substantial radiation [6] and ionization [1] losses. The latter is described by the Seaton formula, improved for ionization from excited states [7]. This leads to a rough interpolation formula without the dependence on the current ionization i number. Unifying the channels of losses for ionization and radiation in lines, we obtain

$$Q^- \; (\text{erg/cm}^3\,\text{s})=7.02\times10^{-16}n_in_e[T(\text{eV})]^{1/2} \; . \tag{13b}$$

Here n_i is the concentration of the heavy admixture ions.

Equating the expressions (13a) and (13b) and using (4b), we can see that heat balance in the case when $T=T_f$ does not depend on temperature is determined only by the ratios S_1/S_p, I_{th}/I, and n_e/n_i. It can be shown readily that

$$n_eS_l/S_pn_i=67I_{th}/I \; . \tag{14}$$

For the real relations $S_l/S_p\simeq0.1-1$, the heavy admixture concentration is 0.1–1 %. For the first value the change of the electron concentration and the plasma density can be ignored, and our assumption about the constant n_e is true for a rather wide range of parameter variation. With the given geometry of the experiment (fixed S_l and S_p) the balance can be obtained by changing the value n_i.

INSTABILITIES AND COMPETITION PROCESSES

Hydrodynamic instabilities of plasma can prevent confinement by a laser beam(s). The laser radiation is spent also for nonlinear optical effects, and they can destroy the beam.

The main hydrodynamic instability is connected with the filamentational self-focusing instability as two sides of the same phenomenon: the ejection of plasma can lead to the separation of a part of the beam from the main beam; as a result the local balance (5) will be set, and it is just the filamentation. Let us derive the condition when the filamentation instability is not developed—it will be the condition of main hydrodynamic instability suppression.

The mechanism of laser beam self-focusing due to the ponderomotive force is well known [2]. In initially homogeneous plasma the power of a beam with smooth transversal distribution and intensity determined by the expression (4b) amounts to $r_{cl}S_i n/2\pi$ of the critical power P_{cr} of self-focusing for hydrogen plasma (r_{cl} is the classical electron radius). For the real values of $S_1 \sim 10^{-5}-10^{-6}$ cm^2 and $n \simeq 10^{20}-10^{22}$ cm^{-3}, this power exceeds the critical one, and self-focusing develops. This threshold can be 4–5 times higher [8] for a beam of nonsmooth transverse profile (as in our case) in homogeneous plasma, but it can also be exceeded. It would seem that this is the self-focusing that sets the limit to the density of the active plasma at the level $10^{20}-10^{22}$ cm^{-3} that determines, in accordance with the Lawson criterion, considerable confinement times and high energy of the laser pulse.

The situation with self-focusing is somewhat different when the plasma is situated only inside the beam (Fig. 1) [9]. At the beam periphery (point 1) self-focusing does not develop due to the small value of the field; in the area of the maximum it does not take place because of small plasma density (the threshold is inversely proportional to the density, point 2). Thus the development of self-focusing is possible within the area of the highest field gradient (point 3). At the beginning of the process, the refractive index in the domains of higher plasma density is less than in other areas because of the inhomogeneities with respect to the azimuthal angle. The laser field is displaced out of these areas into the areas with lower plasma density. The field, increasing in the areas of rarefaction, displaces the plasma further (the force is proportional to $\sim E^2$), and a "goffer" pattern involving areas of higher and lower density is formed at the cylindrical surface of the plasma. For final filamentation the areas of higher density must close around a part of the beam. This occurs when the change in the field amplitude variation due to the self-focusing "goffer" ΔE_{st} at the filament thickness scale $r_{sf}=(P_{cr}/\pi I)^{1/2}$ exceeds the gradient of the field amplitude $\partial E/\partial r$ in the beam. In this case the plasma is displaced not only in the direction of the decrease of the field gradient, as in the case of the goffer development, but in all directions. So, there is a range of the beam power, where the threshold of self-focusing is already exceeded for smooth beams P_{cr}, but still insufficient for the filamentation of a tubelike beam in the specific situation under consideration. From the condition $\Delta E_{sf}/r_{sf} \ge \partial E/\partial r$, using the expression for the plasma refractive index as a function of the field $N=N_0+N_2E^2$, $\Delta E_{sf}/E=\Delta N/N=N_2E^2/N$ (for the formula for N_2 see Ref. [2]), we obtain the criterion of the tubelike beam stability with respect to self-focusing in the case under consideration

$$I \le I_{th}^{*}=\frac{n_{cr}}{n}\left[\frac{16\pi\lambda^2}{N(1-N)^3}\left[\frac{1}{E}\frac{\partial E}{\partial r}\right]^2\right]^{1/3} I_{th} . \quad (15)$$

The value of $(1/E)(\partial E/\partial r)$ is taken at the maximum of the gradient and is somewhat smaller than the half-thickness of the ring. Thus, when focusing into a thin (several tens of micrometers or less) ring, the radiation intensity inside it can exceed I_{th} by several times, but be still less than I_{th}^{*}, and the tube beam will not be eliminated yet because of self-focusing. When using the scheme of duct section, the problem of self-focusing is not crucial, since the length of the caustic of each beam in the plasma can be extremely small (see Fig. 2).

The suggested scheme is free from one of the main hydrodynamical instabilities of magnetic traps—that of the sausage type. In this case the local decrease in density at the plasma boundary (and decrease in its pressure) does not cause additional compression, and, on the contrary, the confining ("compressing") force decreases, i.e., the local balance of forces is always kept.

Since in order to cool down hydrogen plasma it is expedient to utilize the plasma of heavy elements, it would seem that conditions of Raleigh-Taylor instability may be valid as in the usual inertial confinement fusion. The ponderomotive force has to act on the heavy plasma for this instability to rise. Really, the heavy plasma is located inside a hydrogen one (see below for experimental concepts). It has to diffuse to the periphery toward the beam at least (see Fig. 1). It is easy to show that the time of diffusion ≥ 100 ns, which is much more than the pulse duration. Thus it is impossible to expect the Raleigh-Taylor instability development in the problem under consideration.

Main nonlinear effects are the stimulated Brillouin scattering (SBS) and the stimulated Raman scattering (SRS). Both the SBS and the SRS lead to additional reflection of the laser radiation by plasma (the SBS modulation of plasma density is not so significant here). The data of [10] show that due to SBS at KrF laser wavelength, with radiation intensities being greater than 10^{14} W/cm^2, the reflection constitutes 5–10 %, and due to SRS it is 1–3 %. The percent has a tendency to decrease under the intensity rise, and the development of plasma turbulence is considered as the main cause for it [11]. Turbulent velocities of plasma are much less than the velocity of electron oscillation (in the field); therefore the turbulence cannot influence the ponderomotive force. Thus, nonlinear effects do not make the requirements for radiation more strict and do not eliminate confinement and heating.

Let us consider briefly the influence of transversal beam uniformity and coherence on confinement conditions. It is evident that a very small length of coherence simply does not permit one to discuss the ponderomotive force, if the phase of the field breaks down during one oscillation period. However, such lengths of coherence (about the oscillation length of 10^{-6} cm for the KrF laser) do not exist in real laser systems, and the influence of the coherence length on the confinement is small. The influence of intensity is discussed below.

The transversal profile of the laser beam has to be smooth enough in order to prevent opposite transversal plasma flows. Such flows are possible, if the depth of transversal amplitude modulation is large. This modulation in all existing systems is relatively small.

Thus, the main instability of the problem under consideration will be the main hydrodynamic instability and the filamentational self-focusing instability as two sides of the same phenomenon. The criterion (15) gives the conditions for nondevelopment of this instability. Other instabilities and optical nonlinear processes do not influence critically the process of plasma confinement due to the ponderomotive force of laser beam(s).

LONGITUDINAL OUTFLOW

The problem of plasma longitudinal outflow must be considered if no special measures to prevent it are undertaken. In principle, three different schemes are possible in order to control the longitudinal outflow. In the first case plasma is blocked due to additional laser beams cutting the plasma column from both ends. In the second case plasma flows out freely, and its confinement time is equal to L/v_i, where L is the longitudinal dimensional of the confined plasma column. In the third case there is some solid substance in the center of the beam. In this case friction between the plasma and this substance exists, and the minimum outflow time is determined by the viscosity of the plasma and its length. The simplest model is provided by the viscous flow of a fluid near the surface. The value of the fluid velocity v_{ax} at the distance r_0 from the surface is described by the expression

$$v_{ax}=2nT_f r_0/\zeta ,$$

where ζ is the plasma viscosity at the temperature T_f [12].

In the case where the diameter of the central filament is comparable with the transversal plasma dimension, the condition of the plasma nonoutflow can be written as $L/v_{ax} \gg \tau_c$, where τ_c is the confinement time. Substituting the value of v_{ax} to this inequality, one can see readily that this condition has a universal character for the reacting question, since the value $\tau_c n T_f$ is constant. This relationship can be replaced by the more informative geometrical ratio of the plasma column length L to its radius (or transversal dimension) r_0,

$$L/r_0 \gg 2\tau_c n T_f/\zeta=48 . \qquad (16)$$

Taking into account the fact that this relationship involves the maximum velocity of the outflow, and due to the presence of a heavy admixture in the plasma leading to an increase in viscosity, the condition (9) can be simplified by changing the sign $\gg$ for the sign $>$ (though in the case when the radius of the plasma column is much greater than the diameter of the filament, one should use the sign $\gg$ again).

ESTIMATIONS AND EXPERIMENTAL REMARKS

The above considerations lead to two experimental schemes for the relaxation of the proposed idea. The experiment can involve the following. A rod made of a deuterium-tritium mixture, frozen [9] onto a thin wire of a heavy metal, is positioned on the axis of a tubelike laser beam. The rod evaporates and is ionized either by the edges of the main beam, or by additional laser radiation, and then it is confined during the necessary time period determined by the Lawson criterion for the given mixture. Heat transfer from plasma to the central filament due to heat conductivity provides the necessary plasma parameters, on the one hand, and, on the other hand, the supply of thermonuclear fuel to the plasma.

The condition of plasma confinement in the transversal direction determines the minimum intensity of the laser beam. For a KrF laser, I_{th} of the deuterium-tritium reaction is 1.33×10^{17} W/cm^2. Let us analyze how the Lawson criterion is satisfied. It is clear that the density of generated plasma should be maximum for the increase of fusion yield. At the same time the electron density of plasma should be less than the critical one; otherwise the laser radiation would simply be unable to penetrate the plasma. The length of confinement determined by diffraction on the external edge of the beam cannot exceed the absorption length by many orders of magnitude, since the sufficient confinement condition can be satisfied only approximately. Therefore $L_{conf}\sim(1-10)L_a$, $L_a\sim0.1$ cm under $n\sim n_{cr}/2$, $\lambda=248$ nm. Let us choose $n=2n_{cr}/3$. The confinement time should be $\simeq 8$ ns for the density $n=\alpha n_{cr}=2n_{cr}/3$; therefore the laser pulse should not be shorter than 8 ns. This means that additional confinement of plasma in the longitudinal direction is required which can be attained by placing the filament in the center of the plasma.

Let us analyze the possible dimensions (and, therefore, possible energies of laser input and fusion yield) of tubelike beam(s) for the above-mentioned conditions. The relation (15) means that the transversal dimension cannot exceed the value of 25–30 μm, the longitudinal dimension being up to 1 cm. In principle, in order to reduce the necessary laser energy, one should reduce the transversal and longitudinal dimensions down to their minimum values [with the condition (16) being satisfied], which are controlled by the experimental features for tubelike beam focusing.

In order to obtain the thermonuclear energy E_f equal to the laser beam energy E_l, $E_l=16$ kJ must be available, the external radius of the ring being $\simeq 15$ μm. The length of the caustic waist L_c is $\simeq 800$ μm. The maximal value of $L_{conf}\simeq 1$ cm, the radius of the internal ring is ~ 0.2 mm, the ring thickness is ~ 25 μm, $E_l=750$ kJ, and $E_f=9.7$ MJ. The opportunity to increase $L_{conf}>1$ cm is doubtful for a KrF laser; therefore the criterion $E_f/E_l\sim30-1000$ cannot be satisfied in experiments with tubelike beams.

Such experiments may benefit from the utilization of lasers with the smallest wavelength. These requirements are met for excimer lasers or harmonics of Nd-glass lasers. The criterion $E_f/E_l>30-1000$ can be easily satisfied for a tubelike beam at the wavelength $\simeq 0.1$ μm.

Let us consider the scheme with several cylindrically focused beams, intersecting and forming a cavity of a duct section (Fig. 2). The transversal dimensions of the focal area can be several hundreds of times less than the longitudinal dimensions; the criterion (16) and the sufficient confinement condition give for the KrF laser $L_{\text{conf}}=1$ cm; therefore the maximum volume of active plasma is up to 1 cm^3.

The criterion $E_f=E_l$ becomes valid under $E_l=185$ kJ for the closed cubelike cavity (the size of six beams 203×14.2 μm each). If $E_l=5.5$ MJ, $E_f=165$ MJ, then the criterion $E_f/E_l\sim 30-1000$ becomes valid. The maximum dimensions of the beams are determined according to (15) and they are 0.36 cm$\times$60 μm, which gives $E_l=13.8$ MJ, $E_f=1$ GJ. The same results are obtained for open-duct-section cavities.

Let us note also that all existing powerful laser systems are multibeam ones as a principle. Therefore the best geometry for the proposed experiment can be realized when laser beams form a closed spherelike cavity.

Thus the scheme with closed active plasma is suitable for industrial energy production. The experiment may be enhanced by the choice of the number of beams and the cavity shape in order to satisfy the criterion $E_f/E_l>30-1000$ at a smaller value of E_l. An excimer laser or the fourth harmonics of Nd-glass lasers with an efficiency of $\simeq 1-3\,\%$ and an energy $E_l=(1-10)$ MJ simultaneously in several beams allow considerable thermonuclear energy to be obtained.

CONCLUSION

In this study an alternative scheme of plasma confinement in a tubelike laser beam (or a cavity of a duct section formed by several cylindrical beams) due to the action of the ponderomotive force is suggested and analyzed. The conditions when active plasma is free from hydrodynamical instabilities are given. The criterion of self-focusing beam stability is given also. It is shown that competing nonlinear optical effects do not limit the process. The heat balance is satisfied, provided that an additional mechanism is utilized for the removal of heat out of the plasma area, where the absorption of laser radiation takes place. The substance outflow in the longitudinal direction is determined by the plasma viscosity and can be considerably reduced by placing a filament of a heavy substance in the center of the plasma column. The energy of the pulse of laser radiation necessary for plasma confinement accompanied by the satisfaction of the Lawson criterion, lies in the range 1–20 kJ for a KrF or the fourth harmonics of Nd-glass lasers depending on the geometry of the experiment. It is possible to attain the criterion $E_f=E_l$ due to the increase of beam dimensions. In the geometry of duct section cavity formed by several cylindrical beams, a KrF or the forth harmonics of Nd-glass lasers with total energy $\sim 1-10$ MJ and an efficiency of $1-3\,\%$ can be used for industrial energy generation through controlled thermonuclear fusion.

Estimations show that laser energy necessary to provide controlled thermonuclear fusion under this approach is much less than in the scheme of inertial confinement. Additionally, for the suggested scheme the problem of superthermal electrons is not actual. The suggested scheme can be (partially) realized already at the available facilities: "Nova" (LLNL, U.S.A.), "Gekko-12" (ILE, Japan), "Aurora" (LANL, U.S.A.).

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