HIGH-TEMPERATURE HIGH-DENSITY PLASMA FROM A SPECIAL GAS TARGET HEATED BY A LASER

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The feasibility of producing dense plasma at thermonuclear temperatures is studied by postulating a special gas target exposed to a high-power laser beam. It is shown that a magnetic field of the order of 10^6 Oe requires a 3×10^5 J, $\sim10^{-7}$ sec laser pulse in order to obtain a positive energy yield (relative to the laser energy) from a fusion reaction in a mixture of deuterium and tritium.

In view of the advances in quantum electronics and the approaching practicability of controlled thermonuclear reactions, the problem of laser application to the production of dense fusion-temperature plasma has recently been the subject of intensive discussion. At the present time there are several methods of using lasers to produce and heat plasma.

The first method[1,2] consists of focusing a high-power laser beam on a semi-infinite target surface of a solid or liquid mixture of heavy hydrogen isotopes: deuterium and tritium. According to the second method the target is a small condensed particle suspended or slowly falling in vacuum across the focal region of the laser beam.[3] The third calls for the use of a gaseous medium that, when exposed to a focused laser beam, undergoes an optical breakdown and a subsequent heating of the plasma.[4] Finally, the fourth method is based on the use of CO_2 lasers emitting at $\lambda = 10.6\,\mu$ that in principle makes it possible to heat efficiently plasma with a density of 10^{19} cm^{-3}. In this case even in the range of fusion temperatures one can consider magnetic containment of plasma by reasonable magnetic fields. Nevertheless the last method is difficult to entertain today because the necessary experimental base is still in its inception in spite of the additional attraction this method offers in the feasibility of suitable lasers with high efficiency reaching 10–20%.

The first two methods claim the most attention and optimism because of the proposed use of super-dense plasma with $n_i \approx 5\times10^{22}$ cm^{-3}. These two approaches were the subject of a large number of recent theoretical and experimental papers and they were the most successful so far.[2,5-7] Super-dense plasma allows for a significant reduction in the volume of the material. On the other hand, this in turn causes an excessively rapid cooling of plasma upon expansion into vacuum, calling for laser pulses of $\tau \gtrsim 10^{-9}$ sec. The final evaluation of these two methods, however, is not yet possible, owing to our ignorance of the interaction between intense laser beams with super-dense plasma, electron thermal conductivity in dense plasma with large density and temperature gradients, and some other problems. An optimistic estimate for these two methods holds that a positive yield of thermonuclear energy relative to the laser beam energy requires a laser with 10^6 J per pulse 10^{-9} sec long, assuming that the entire laser energy is completely contained in the necessary plasma volume. Less optimistic estimates lead to a laser pulse energy of 10^7–10^8, and even 10^9 J.

As long as the upper limit of neodymium glass laser energy forecast for the next 5–10 years is confined to the interval of 10^4–10^6 J,[7] the feasibility of this approach remains an open question. Therefore we consider it necessary to analyze all the methods in greater detail and to continue intensive research in all possible directions discussed above, including combined methods of producing hot plasma in which lasers are used to fill open and closed magnetic bottles with plasma. In this situation it seems to us that the third method based on the use of gaseous target has been undeservedly avoided by specialists. It undoubtedly presents its difficulties but their successful solution can clear the way to advantages that may prove to be decisive.

One of the possibilities of this method that is usually considered by the specialists is simply the use of an unlimited gaseous medium of a mixture of heavy hydrogen isotopes. The focused laser beam induces an optical breakdown in such a medium with a subsequent heating of the resulting plasma by the laser beam (so-called laser spark). Unfortunately this simple scheme does not promise very high temperatures, T_i = 1–10 keV. In fact, according to the results of research on the laser spark obtained in our laboratory beginning with 1963, and also to the results of other authors,[8-11] the physical mechanism of the phenomenon is today clear in general outline.

If the radiation flux density in the focal region considerably exceeds the breakdown threshold, the breakdown region expands rapidly down the cone of light against the laser beam and the breakdown front moves far enough from the region of maximum radiation intensity. The laser radiation is absorbed mainly by the breakdown front and the power density at the front turns out to be low, owing to the rapid displacement of the front at the time of the power peak of the laser pulse. Several mechanisms govern the motion of the laser spark front and each dominates under different experimental conditions: hydrodynamic, breakdown wave, motion due to radiative thermal conductivity, or various combinations of these. Thus the main difficulty of producing high-temperature plasma in this scheme is the rapid increase of the volume occupied by plasma, i.e., a rapid increase of the number of plasma particles partaking of the laser pulse energy. Therefore the maximum

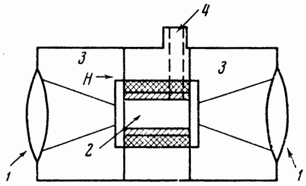

Diagram of special gaseous target with magnetic field.

temperatures that could be obtained by this method amount to $T_e \approx 300$–400 eV.[12]

It is clear that the main cause of this difficulty is the fact that for gas pressures of the order of one atmosphere and above at optical frequencies the breakdown threshold is too low relative to the power flux density necessary to heat the plasma rapidly to thermonuclear temperatures. It would seem that a natural approach to this undesirable phenomenon would consist in reducing the laser pulse length down to the picosecond range. This considerably increases the breakdown threshold intensity, while the length of the wave train amounts to fractions of a millimeter. Unfortunately even in that case nature refuses to cooperate. Thus when considerable energy is stored in the pulse the radiation intensity increases to the point of generating other effects, such as self-focusing, which again produce breakdown in the form of a long string or rather a large number of small discharges along the beam as the laser pulse travels in the medium.[13] Consequently this approach too offers little promise.

To overcome these difficulties we propose to use a bounded gaseous target in the form of a cylindrical channel filled with gas inside a heavy jacket (see the figure). Focusing optics 1 concentrate the laser radiation in the focal caustic, whose axis coincides with target gas channel 2. Both end faces (or one face) of the channel are covered with transparent film to ensure high vacuum in the remainder of chamber 3. The channel can also be left open at one or both ends if gas is continuously evacuated from the remainder of the chamber and excess gas pressure is maintained in the channel itself by gas supply line 4. This system eliminates the main disadvantage of the unlimited gaseous medium system. Furthermore, there is no radial expansion of hot plasma, owing to the heavy jacket that permits only one-dimensional expansion along the axis; with proper channel geometry this can ensure an adequately large containment time τ.

We analyze the conditions that can be expected to produce a positive fusion energy yield relative to the laser emission energy, and the needed energy and length of the laser pulse. For a 50% mixture of deuterium and tritium, the fusion energy exceeds the kinetic energy stored in plasma if

$$\tfrac{1}{4} n_i^2 \langle \sigma v_i \rangle \tau V \Delta \geqslant 2 n_i k T V. \quad (1)$$

The total energy emitted in an elementary act of the $D + T \rightarrow He^4 + n$ reaction, taking the energy removed by the neutron into account, is $\Delta = 17.6$ MeV. For an ion temperature $T_i = 10^8\,°K$ corresponding to the minimum of (1), we have $\langle \sigma v_i \rangle = 10^{-16}$ cm^3/sec and condition (1) leads to the well-known requirement

$$n_i \tau \geqslant 0.4 \cdot 10^{14}\ \text{cm}^{-3}\text{sec}. \quad (2)$$

Since one of the advantages of the gaseous target is that it permits operation at plasma densities that render the beam reflection negligible, i.e., when $\nu > \nu_{pl}$, we arrive at the condition for the limiting plasma density $n_i = 2n_D = 2n_T = n_e \leq 10^{21}$ cm^{-3} for a neodymium glass laser. Consequently to satisfy (2) the containment time should be $\tau \geq 4 \times 10^{-8}$ sec. In the case of one-dimensional axial expansion of the plasma, the expansion time is $\tau = l/v_i$, where l is the length of the channel and v_i is the thermal velocity of ions, $v_i = 8 \times 10^7$ cm/sec for the deuterium-tritium mixture at $10^8\,°K$. Consequently the channel length necessary to ensure inertial containment should be $l_{cr} \geq \tau v_i = 3$ cm.

However since the absorption of laser radiation by plasma heats the electrons while the ions are heated via electron-ion collisions, the real gasdynamic expansion time is determined by the electron-ion thermalization time τ_{ei}:

$$\tau_{ei} = 0.73 \cdot 10^3 \frac{T^{3/2}}{n_e \ln \Lambda}. \quad (3)$$

For $T_e = 10^8$ K and $n_e = n_i = 10^{21}$ cm^{-3} we obtain $\tau_{ei} = 7.3 \times 10^{-8}$ sec and the length of the channel is $l_{cr} \approx 6$ cm. Effective feeding of the optical laser energy to the plasma requires that the characteristic length of laser light absorption by the plasma be not greater than the length of the channel, i.e., $l_{cr} \geqslant 1/\alpha$. The coefficient of radiation absorption α in plasma due to free-free transitions, for the neodymium laser frequency and neglecting nonlinear effects, is

$$\alpha = 10^{-34} \frac{Z^3 n_i \ln \Lambda}{T_e^{3/2}}. \quad (4)$$

For $T_e = 10^8$, $n_i = 10^{21}$, and $Z = 1$, we have $\alpha \approx 1$ cm^{-1} and the requirement $l_{cr} > 1/\alpha$ is met.

These computations allow us to estimate the necessary energy input to the plasma per unit cross sectional area of the channel

$$E_{sp} = 2 n_i k T l = 1.7 \cdot 10^7\ \text{J/cm}^2 \quad (5)$$

The length of the laser pulse should not exceed the plasma containment time $\tau = 70$ nsec; consequently the laser radiation density should exceed $I \geqslant 2 \times 10^{14}$ W/cm^2.

We now consider the necessary channel diameter, since it governs the total laser energy. While it is assumed that the heavy jacket ensures an effective containment of the radial expansion of the plasma, its presence nevertheless causes the plasma to cool via thermal conductivity. If we assume that the rate of heat transfer from the plasma to the jacket is determined mainly by electron thermal conductivity of the plasma, we can quite naturally arrive at the fundamental condition for the high-temperature plasma in the channel: the rate of energy transfer to the channel wall due to electron thermal conductivity should be less than the rate of energy transfer from the electrons to the ions. This condition can be written in the form:

$$\tau_{ei} < \tau_{\text{el. therm.}} \quad (6)$$

The electron thermal conductivity time $\tau_{\text{el.therm.}}$ is determined by the heat capacity of the plasma $c_V = 2(n_e + n_i) \times 10^{-16}$ erg/cm^3-sec, the coefficient of electron thermal conductivity $\eta_e = 1.3 \times 10^{-5}\, T^{5/2}/Z \ln \Lambda$

erg/deg-cm-sec, and the plasma channel radius r in the following manner:

$$\tau_{\text{el. therm.}} = r^2 c_v / \eta_e. \quad (7)$$

Condition (6), taking (3) and (7) into account, leads to the requirement $r^2 > 30\ \text{cm}^2$ for the radial dimension of the channel, i.e., the transverse dimension turns out to be of the order of the axial dimension and the total energy in the laser pulse should be $E > 10^9$ J.

If by virtue of a relatively modest axial magnetic field we can realize the case in which thermal conductivity in the radial direction is mainly determined by the ions, then the coefficient of thermal conductivity η_i is $\sqrt{m_i/m_e}$ times lower. An effect analogous to that of the axial magnetic field can be obtained by blocking electron conductivity at the plasma-jacket interface and using a double electric layer.[14] Nevertheless even under these conditions the cross sectional area of the channel remains of the order of 1 cm^2 and thus the necessary laser pulse energy amounts to $\sim 2 \times 10^7$ J.

The imposition of the axial magnetic field appears to be the most promising in this approach. The field should be such as to render the radial magnetic pressure low enough to be neglected and yet high enough to reduce perceptibly the ionic thermal conductivity in the radial direction. In this case the same physical considerations that led to (6) can be used to write the high-temperature plasma condition in the form

$$\tau_{ei} < \tau_{\text{ion}\perp}. \quad (8)$$

Here the thermal diffusion time $\tau_{\text{ion}\perp}$ due to ionic thermal conductivity across the magnetic field is determined similarly to (7) from

$$\tau_{\text{ion}\perp} = r^2 c_v / \eta_{i,\perp}. \quad (9)$$

According to the calssical expression, the ionic thermal conductivity $\eta_{i,\perp}$ is

$$\eta_{i,\perp} = \frac{1.3k^2 n_i T_i}{m_i \omega_i^2 \tau_{ii}} = \frac{2.5 \cdot 10^{-32} n_i T_i}{m_i \omega_i^2 \tau_{ii}}. \quad (10)$$

Then, considering (9), (10), and that $\tau_{ei} = \sqrt{m_i/m_e}\,\tau_{ii} = 60\tau_{ii}$ and the Larmor ionic frequency is $\omega_i = 9.6 \times 10^3\ H m_e/m_i$, condition (8) can be written in the form

$$r^2 > 56 T_i / H^2. \quad (11)$$

It is interesting that (11) turns out to be independent of n_e and n_i. Assuming that $H = 10^6$ Oe, then for $T_e = T_i = 10^8$ °K we find that (8) and (11) are satisfied for $r^2 > 0.5 \times 10^{-2}\ \text{cm}^2$.

Consequently the proposed method makes it possible to obtain a positive fusion energy yield relative to the laser pulse energy from a laser with a total energy $E \approx 3 \times 10^5$ J and a pulse $\tau = 70$ nsec long and with an axial magnetic field $H = 10^6$ Oe. The gaseous target should constitute a bounded channel in vacuum in a heavy jacket 1.5 mm in diameter and about 6 cm long filled with a mixture of gaseous deuterium and tritium under a total pressure of about 20 atm ($n_i \approx 10^{21}\ \text{cm}^{-3}$).

Assuming that the classical mechanism of ionic thermal conductivity in magnetic field is disturbed under conditions of a super-dense hot plasma, owing to turbulent instabilities, the magnetic thermal insulation is still effective in a boundary layer of thickness $\Delta r = 2\rho r_i$, where $\rho > 1$ is a numerical coefficient and r_i is the Larmor radius of the ions. Then in place of (8) we can formulate the hot plasma condition in the form

$$Q_{ei} > Q_{\text{therm}\perp} \quad (12)$$

Here the heat flow $Q_{\text{therm}\perp}$ across a lateral boundary Δr thick with a temperature discontinuity $(T_i - T_e)$ amounts to (per unit length of the cylinder)

$$Q_{\text{therm}\perp} = 2\pi r \frac{(T_i - T_0)}{\Delta r} r_{i,\perp} = \frac{1.4 \cdot 10^{-17} \pi r n_i \ln\Lambda}{\rho H}, \quad (13)$$

and the energy flow Q_{ei} from electrons to ions in a unit length cylinder of radius r is

$$Q_{ei} = \pi r^2 \frac{n_e (T_e - T_i) k}{\tau_{ei}} = 2 \cdot 10^{-19} \frac{\pi r^2 n_e^2 (T_e - T_i) \ln\Lambda}{T_e^{3/2}}. \quad (14)$$

Setting $T_i - T_0 = T_i$, and $T_e - T_i \approx T_e$ we find that (12) is satisfied for

$$r > 0.7 \cdot 10^2 T_e^{1/2} / \rho H. \quad (15)$$

For $T_e = 10^8$ °K, $H = 10^6$ Oe, and $\rho \approx 2$ from (15) we have $r \approx 0.3$ cm and according to (7) the total energy in the laser pulse should amount to $E = 5 \times 10^6$ J. According to (15), however, the final estimate depends on coefficient ρ. In fact (13) is analogous to the empirical formula of Bohm and coefficient ρ determines the extent to which turbulent instabilities disrupt the classical thermal conductivity in a magnetic field.

In any case, the proposed approach holds that the actual energy of the laser pulse necessary to obtain positive thermonuclear yield lies somewhere within the interval $3 \times 10^5 - 5 \times 10^6$ J, depending on the nature of instabilities that may occur in such a plasma. The absolute laser energies obtainable under these conditions, taking into account the possibility of working with relatively long pulses of $\tau = 70$ nsec, indicate that in principle controlled fusion reactions with the aid of lasers are not entirely hopeless. Furthermore the estimates of the requisite laser energies show that the gaseous target with a magnetic field may prove more promising than other methods.

In conclusion we note that the proposed system of a target with a radial inertial containment, magnetic thermal insulation, and axial gas flow into vacuum can also be used for plasma heating in electron beam experiments that are susceptible to excessive beam retardation in dense plasma, owing to collective effects. In that case the experimenter is also given control of one more parameter of the original target, gas density, by varying the pressure in the channel, a parameter that may turn out to be quite significant.

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