# *Production of a High Temperature Deuterium Plasma by Laser Heating of a Special Gas Target*

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Calculations are presented of the electron temperature in a laser-heated deuterium plasma. A special gas target is considered in the form of a cylindrical channel filled with gaseous deuterium and bounded on the ends by thin films. For various initial gas pressures and a fixed energy in the laser pulse, an optimization is carried out of the experimental parameters such as pulse duration and channel diameter (i.e., sharpness of focusing) for various values of external longitudinal magnetic field. In the optimal configuration the plasma temperature and neutron yield are calculated as a function of the energy in the laser pulse.

## INTRODUCTION

IN an earlier paper[1] we proposed a new experimental arrangement for obtaining a dense plasma at thermonuclear temperatures with laser heating, in which it was planned to use a gas target in the form of a solid cylindrical shell filled with gas and bounded on the ends by thin films. This arrangement assures inertial confinement of the plasma with a one-dimensional motion along the axis of the cylinder, since radial motion is limited by the heavy shell. It was proposed to reduce the loss by thermal conductivity in the radial direction substantially by application of a pulsed longitudinal magnetic field. The evaluations presented[1] showed that this arrangement in principle permits the hope that a nuclear synthesis reaction can be obtained with a positive yield relative to the applied laser energy for laser energies of $10^5-10^6$ joules and a laser pulse duration no greater than 70 nsec. Comparison of the estimates made for this scheme with those for the previously proposed heating method involving a solid target[2,3] shows that the new scheme may turn out to be no less promising.

However, in view of the fact that a number of the assumptions used in the papers cited above have not yet been justified experimentally, and that experimental verification of the promise of these methods can be carried out in the near future at lower levels of laser energy, it appeared to us desirable to make a more detailed analysis of the dependence of the achievable plasma temperatures and neutron yield on the laser pulse energy. Here an estimate is made for each energy value of the optimal values of laser pulse duration and target channel diameter, i.e., required sharpness of focus. Calculations were made for various values of initial gas pressure in the target and for various magnetic field strengths. This analysis will be useful also for design of experiments on laser heating of a plasma, since it can serve to some extent as a guide both in development of an experimental program and for comparison of experimental results with theory.

## 1. CALCULATION FOR THE CASE OF NO MAGNETIC FIELD, H = 0

In the case of zero magnetic field, there is no magnetic thermal isolation of the plasma in the radial direction. Therefore in this case the role of the heavy wall of the channel may turn out actually to be very small. In fact, the channel wall can limit the radial motion, but at the same time we require that the loss by thermal conduction in the radial direction is not sufficient to cool the heated volume before the gas-dynamical escape of the plasma begins. This requirement leads to equality of the longitudinal dimension of the channel being heated and its radial dimension. Consequently, the main feature of the proposed scheme—inertial confinement of the plasma with sharply defined one-dimensional motion along the channel axis—practically disappears in the case of zero magnetic field and we arrive at a method of calculation similar to that discussed by Basov and Krokhin[3] and Shearer and Barnes[4] for simple inertial confinement of a plasma with employment of a semi-infinite solid target.

The time of inertial confinement of a plasma with density $n_e$ in which the electrons are instantaneously heated to a temperature $T_e$ is equal to the time of electron-ion thermalization $\tau_{ei}$, which for the heavy hydrogen isotopes is[5]

$$\tau_{ei} \approx 7.3\cdot 10^2 T_e^{3/2}/n_e \ln\Lambda. \quad (1)$$

During this time, as a result of the electronic thermal conductivity $\eta_e$, the size of the heated region of plasma $r$ is determined from the relation $r^2 = \tau_{ei}\,\eta_e/c_V$ and is equal to

$$r = 0.5\cdot 10^7 T_e^2 / n_e \ln\Lambda, \quad (2)$$

where the specific heat of the plasma is $c_V = 2(n_e + n_i) \times 10^{-16}$ erg/cm³, and $\eta_e = 1.3\times 10^{-5} \times T_e^{5/2}/Z \ln\Lambda$ erg/cm-sec-deg.

Consequently, laser energy applied to a plasma for a time $\Delta t < \tau_{ei}$ leads to heating of a volume of plasma $V = \frac{4}{3}\pi r^3$ to a temperature $T_e$, and according to Eq. (2) we obtain from the energy balance equation $E = Vc_V T$ the expression

$$E = \frac{1.5\cdot 10^5 T_e^7}{n_e^2(\ln\Lambda)^3}. \quad (3)$$

Hence it follows that in this scheme for 100% efficiency of the contribution of the laser energy to the kinetic

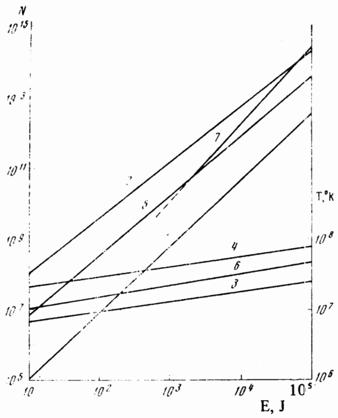


FIG. 1. Plots of total neutron yield N (curves 1, 2, 5, 7) and maximum plasma temperature T (curves 3, 4, 6) as a function of the energy in the laser pulse. Neutron yields are given for the cases: 1–n = $10^{21}$ cm$^{-3}$, H = 0; 2–n = $5 \times 10^{22}$ cm$^{-3}$, H = 0; 5–n = $10^{21}$ cm$^{-3}$, H ≠ 0; 7–n = $10^{21}$ cm$^{-3}$, H = $10^6$ G.

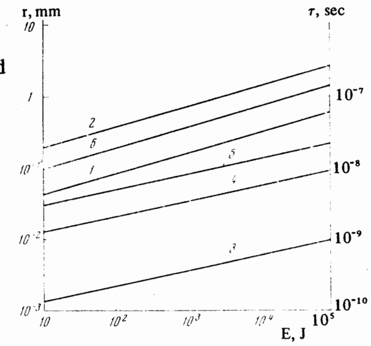


FIG. 2. Radial size r of heated plasma (curves 1, 2, 6) and time of inertial containment $\tau_{ei}$ (curves 3, 4, 5) as a function of the energy in the laser pulse. The channel radii correspond to the cases: 1–n = $5 \times 10^{22}$ cm$^{-3}$, H = 0; 2–n = $10^{21}$ cm$^{-3}$, H = 0; 6–n = $10^{21}$ cm$^{-3}$, H ≠ 0.

energy of the plasma, the maximum achievable temperature $T_e$ is

$$T_e \approx T_i \approx 0.48[n_e^2 E]^{1/7}. \quad (4)$$

The total neutron yield N from the heated volume of a deuterium plasma, as is well known, is determined by the relation $N = \frac{1}{2} n_i^2 \langle \sigma v \rangle \tau V$, where $\tau$ is the duration of the reaction, which can be assumed equal to $\tau_{ei}$. Using the Gamow–Teller expression for the cross section $\langle \sigma v \rangle$ for the D–D reaction

$$\langle \sigma v \rangle = \frac{1{,}3 \cdot 10^{-9}}{T^{2/3}} \exp\left\{-\frac{4.24 \cdot 10^3}{T^{1/3}}\right\},$$

substituting the value of $T_e$ from Eq. (4), $\tau_{ei}$ from Eq. (1), and determining V from Eqs. (2) and (4), we obtain the dependence of the total neutron yield N on the energy in the laser pulse E in the form

$$N = 1.2 \cdot 10^8 \frac{E^{41/42}}{n^{1/21}} 10^{-2365/[n^2 E]^{1/21}}. \quad (5)$$

The values of neutron yield N calculated from this expression as a function of the energy in the laser pulse for two values of plasma density n = $10^{21}$ cm$^{-3}$ and n = $5 \times 10^{22}$ cm$^{-3}$ are shown in the form of curves 1 and 2 in Fig. 1. The corresponding values of maximum plasma temperature according to Eq. (4) for these densities are determined by curves 3 and 4.

Values of the region of plasma heating r (curves 1 and 2), which determine the optimal size of the focusing radius of the radiation, and also the limiting durations of the laser pulse $\Delta t \approx \tau_{ei}$ (curves 3 and 4), estimated from formulas (2) and (1) with use of Eq. (4), are shown for the same plasma density values in Fig. 2.

## 2. CALCULATION FOR THE CASE WITH A MAGNETIC FIELD SUPPRESSING ELECTRONIC THERMAL CONDUCTION IN THE RADIAL DIRECTION

Inclusion of a longitudinal magnetic field along the channel axis in a solid shell filled with hot plasma can substantially reduce the thermal conduction of the plasma in the radial direction and change the thermal balance. Obviously, this effect of the magnetic field becomes appreciable when the condition $\omega_{ee}\tau_{ee} \gtrsim 1$ is satisfied, where $\omega_{ee} = 1.76 \times 10^7$ H is the cyclotron frequency, and $\tau_{ee} = 0.266\, T_e^{3/2}/n_e \ln \Lambda$ is the self-collision time for electrons.[5]

Practical interest is presented by magnetic fields for which the electronic thermal conduction transverse to the magnetic field is completely suppressed and the heat flux in the radial direction is determined by the ionic thermal conduction. Since the ionic thermal conductivity $\eta_i$ is $\sqrt{m_i/m_e} \approx 60$ times weaker than the electronic conductivity, and the electronic thermal conductivity transverse to the field $\eta_{e\perp}$ falls off inversely in proportion to $(\omega_{ee}\tau_{ee})^2$, the required condition $\eta_{e\perp} < \eta_i$ can be written in the form $(\omega_{ee}\tau_{ee}) > 10$. Hence, with insertion of the expressions for $\omega_{ee}$ and $\tau_{ee}$, we obtain an estimate for the required magnetic field value H:

$$H \geqslant 2.5 \cdot 10^{-5} n_e / T_e^{3/2}. \quad (6)$$

In the presence of a field satisfying condition (6), the energy balance of the laser-heated plasma in the channel is carried out by the same scheme as in the preceding case, except that the effective radius of the heated plasma (and also of the channel) must be evaluated from the expression $r^2 = \tau_{ei}\eta_i/c_v$, where the ionic thermal conductivity of a hydrogen plasma is $\eta_i = 3 \times 10^{-7} T_i^{5/2}/\ln \Lambda$. Then the radial heated dimension $r_1$ is

$$r_1 = 0.7 \cdot 10^6 T_i^2 / n_e \ln \Lambda. \quad (7)$$

Since the longitudinal heating dimension r is determined as before by Eq. (2), the total volume is

$$V = \pi r_1^2 r = \frac{0.8 \cdot 10^{19} T_i^4 T_e^2}{n_e^3 (\ln \Lambda)^3}$$

and the energy balance equation is written in the form

$$E = V c_v T_e = \frac{3.2 \cdot 10^8 T_i^4 T_e^3}{n^2 (\ln \Lambda)^3} \approx \frac{3.2 T_e^7}{n_e^2}. \quad (8)$$

It follows from (8) that for a 100% contribution of the laser energy to a plasma in a channel of radius $r_1$ the maximum temperature will be

$$T_e \approx T_i = 0.85 (n_e^2 E)^{1/7}. \quad (9)$$

The total neutron yield in this case turns out to be

$$N = \frac{1.3 \cdot 10^3 E^{41/42}}{n^{1/21}} 10^{-1950/[n^2 E]^{1/21}}. \quad (10)$$

Calculation of the total neutron yield N and maximum temperature T as a function of laser energy E for a density n = $10^{21}$ cm$^{-3}$ is shown in the form of curves 5 and 6 in Fig. 1. The minimal durations of the laser pulse $\Delta t = \tau_{ei}$ and the radial dimension of the channel $r_1$ for this case are determined by curves 5 and 6 of Fig. 2, which were calculated from Eqs. (1) and (7) with inclusion of (9).

The required value of longitudinal magnetic field satisfying condition (6) is determined by the values of $T_e$, i.e., decreases with increasing laser energy and for a density $n = 10^{21}$ cm$^{-3}$ lies in the range from $6 \times 10^5$ G to $10^5$ G for a range of energy in the pulse from 10 to $10^5$ joules. As we see, the magnetic field strength necessary to achieve this case is technically quite achievable at the present time. We note that these calculations are applicable also in the case in which there is a substantial blocking of the electronic thermal conduction at the boundary between the plasma and the solid shell as the result of a double electric layer.[6]

## 3. CALCULATION FOR THE CASE WITH A MAGNETIC FIELD DECREASING THE IONIC THERMAL CONDUCTION IN THE RADIAL DIRECTION ACCORDING TO THE CLASSICAL LAW

If sufficiently high magnetic fields are used, it is possible to suppress not only the electronic, but also the ionic thermal conduction in the radial direction. This case is realized when the condition $\omega_i \tau_i \gtrsim 1$ is satisfied, where $\omega_i = 9.6 \times 10^3$ H/A is the cyclotron frequency for ions and $\tau_i = 11.4\sqrt{A}T^{3/2}/nZ^4 \ln \Lambda$ is the self-collision time for ions.[5] The condition $\omega_i\tau_i \gtrsim 1$ for deuterium can be satisfied for

$$H \geqslant 1{,}3 \cdot 10^{-4} n_i / T_i^{3/2}.$$

When this condition is satisfied, in the method of calculation which we have adopted it is possible to use the classical expression for the ionic thermal conductivity transverse to the magnetic field,[5] $\eta_{i,\perp} = 2.7 \times 10^{-16} n_i^2 T_i^{1/2}$. Then the radius of the heated plasma is determined, as in the case above, from the equation $r_2^2 = \tau_{ei}\eta_{i,\perp}/c_v$ and, on the assumption $T_e \approx T_i$, turns out to be

$$r_2^2 = 48T_e / H^2. \qquad (12)$$

When we take into account Eq. (12) and the fact that the size of the heated region along the field is given as before by Eq. (2), from the energy balance equation we obtain $E = 3 \times 10^{-8}T^4/H^2$, from which it follows that

$$T = 76(H^2E)^{1/4}. \qquad (13)$$

The expression for the total neutron yield can be written in the form

$$N = 5{,}7 \cdot 10^7 \frac{E^{23/24}}{H^{1/12}} 10^{-437/[H^2E]^{1/12}}. \qquad (14)$$

As can be seen from Eqs. (12)–(14), the radial size of the channel, the plasma temperature, and the total neutron yield in this case do not depend on the plasma density and are completely determined by the energy in the laser pulse E and the magnetic field strength H. It is true that we must recall that this is valid for the condition $\omega_i\tau_i \gg 1$, and according to Eq. (11) the value of the required magnetic field depends strongly on n.

A curve of the neutron yield as a function of the laser pulse energy for $H = 10^6$ G is shown in Fig. 1 (curve 7).

## 4. CONCLUSION

Comparison of the plots of Figs. 1 and 2 for the three cases discussed above shows that use of pulsed magnetic fields for magnetic thermal isolation in combination with inertial confinement of the plasma by a heavy shell turns out to be quite promising even for comparatively moderate fields $H \approx 5 \times 10^5$ G and over the entire range of laser energy. If we take into account that when a gas target is used in this arrangement, it is possible to use nanosecond laser pulses, in which the energy removed from the same apparatus turns out to be substantially higher than in a picosecond pulse, and the stability of all the optical elements is also higher, the attractiveness of this arrangement is even greater. Furthermore, at all levels of laser energy the required sharpness of focus (the radial dimension of the channel) in the case of a gas target turns out to be within the range of values easily achieved by means of standard elements, while the optimal operation with a solid target poses very difficult problems in just this direction.

It is interesting to note that, both in the case $H = 0$ and for moderate fields (see Sec. 2), the slope of the curves of neutron yield as a function of laser pulse energy turns out to be identical and indicates that $N \sim E^{3/2}$. This is in good agreement with the experimental dependence obtained by the French authors.[7,8]

In strong magnetic fields (see Sec. 3) the neutron yield curve varies more abruptly ($N \sim E^2$). This may also turn out to be important in the transition to the region of higher laser energies in the future and for use of magnetic fields higher than $10^6$ G.

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