THERMONUCLEAR GAIN OF ICF TARGETS WITH DIRECT HEATING OF IGNITOR

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As the way of decreasing of the driver energy which is needed for ignition of the LCF targets, the conception of separation of the process of compression of the main mass of the fuel and the process of heating of the ignitor is suggested. Thermonuclear gain of the target with direct heating of the ignitor is calculated. It’s shown that using the target with direct heating of the ignitor may lead to considerable decreasing of the driver energy: in (10-20) times for “breakeven,” and in (5-10) times for thermonuclear gain of 100-300 in comparison with the traditional conception of simultaneous compression and heating of the ICF target.

Introduction

The bulk of the energy in the target for thermonuclear inertial controlled fusion (ICF), with parameters corresponding to ignition, goes to its internal part — the ignitor — which can be heated to thermonuclear temperature. If the ignitor of a spherical target occurs in the course of compression of the entire mass of the fuel by the piston shell accelerated by a laser or a beam of ions, the efficiency of conversion of the energy of the internal source (driver) into ignitor energy does not exceed (8-12)%. This value is determined by the coefficient of absorption of the driver energy in the target, 70-80%, and by the coefficient of hydrodynamic target transfer — 10-15%.

According to numerical calculations [1, 2], to achieve a target gain (a ratio of thermonuclear energy to driver energy) of ~ 100 the required laser energy is about 10 MJ, and a “breakeven” gain of ~ 1 calls for 100 kJ.

By way of a method of lowering the driver energy needed to ignite the ICF target we propose the concept of separating the compression of the bulk of the thermonuclear matter from the heating of the ignitor. This concept calls for successive action on the target by pulses from two drivers. The pulse of the first effects “cold” compression of the entire mass of the spherical target in a hydrodynamic regime close isentropic. The pulse from the second driver (laser or ion beam) effects rapid direct heating of the ignitor at instants of time lose to the instant of maximum compression of the target by the action of the pulse from the first driver.

In contrast to the first stage of the process, target compression, the ignitor can be directly heated highly effectively by transforming the energy of the second driver into near-unity internal energy of the plasma. The target, the construction of which ensures the possibility of directly heating the igniter, can be called a “worn through ball.”

We consider here mainly the energy aspects of the concept of the first heating of the ignitor. We calculate the coefficient of thermonuclear gain of the “worn through ball” target, and determine for the target and for both drivers the parameters corresponding to reaching gains of ~ 1 and ~ (10^2-10^3).

1. “Cold” Compression

The final density of the thermonuclear matter compressed by a heavy shell accelerated by a laser pulse is determined from two conditions. Firstly, at the instant of maximum target compression the kinetic energy of the non-evaporated part of the shell is equal to the total internal energy of the shell and of the fuel. Secondly, the pressures of the shell and of the fuel are also equal at that instant of time. For the equation of state of the shell and of the thermonuclear matter

\[ P_f(s) = P_f^0 \frac{\delta_f(s)}{f(s)} \]
in which \( P_{f(o)}^0 \) and \( \delta_{f(o)}^0 = \rho_{f(o)}^0/\rho_{f(o)}^0 \) are respectively the cold-pressure constant and the degree of compression of the fuel (shell) while \( \rho_{f(o)}^0 \) and \( \rho_{f(o)}^0 \) are respectively the final and initial densities of the fuel (shell), we easily obtain

\[
\delta_f = \frac{E_c}{\left(\frac{P_f^0}{\rho_f^0}\right)} \left(\frac{M_f + \frac{M_s}{4}}{E_c}\right)^{-1} \tag{1}
\]

In this expression \( E_c = \eta_c E_{co} \) are the energy consumed by target compression (it is equal to the kinetic energy of the unevaporated part of the shell); \( \eta_c = \eta_h \eta_a \) is the coefficient of conversion of the laser energy into kinetic energy of the shell, \( \eta_h \) is the coefficient of absorption of the laser-emission energy; \( \eta_h = M_s \mu_{2/3} \eta_{ca} \) is the coefficient of hydrodynamic transfer [3]:

\[
\eta_h = \left[3(2\gamma - 1)/9(3\gamma - 1)\right]^{1/3} (2\mu - 1) \mu^{-3/2}
\]

\[
\alpha = R \rho_{f(c)}/\Delta \rho_{f(c)}, \mu = [(1 + \alpha/3) \rho_{f(c)} - \alpha^{1/2} \rho_{f(c)}]^{1/3}, R \text{ and } \Delta \text{ are the initial values of the radius and thikness of the shell, respectively, } \rho_{f(c)} \text{ is the critical density, and the final values of the shell mass and velocity are:}
\]

\[
\begin{align*}
M_s &= \left[1 - (2/3)(\alpha \mu)^{1/3}\right] M_s, \\
\end{align*}
\]

\[
\begin{align*}
M_{f(c)} &= \frac{3M_f}{4\pi \delta_f \rho_f^0} \left(\frac{M_s}{2E_c}\right)^{1/2}, \\
\end{align*}
\]

\[
\eta_{ca} \text{ are respectively the energy and intensity of the laser radiation absorbed in the target.}
\]

2. Direct Heating of the Ignitor

The energy required for the direct heating of the ignitor is determined from two conditions of the target heating. The first is that the efficiency of the thermonuclear combustion of the ignitor during the lifetime \( \tau_c \) of the compressed target be sufficient to heat the remaining part of the fuel by \( \alpha \) particles to a temperature close to that of the ignitor. The second condition is the requirement that the ignitor temperature be conserved during the time \( \tau_c \) or, in other words, this condition can be formulated as the requirement that the energy loss in the ignitor be compensated by heating the ignitor with \( \alpha \) particles by electronic heat conduction.

Recognizing that the time of inertial containment of the cold compressed target is

\[
\tau_c = \left(\frac{3M_f}{4\pi \delta_f \rho_f^0}\right)^{1/3} \left(\frac{M_s}{2E_c}\right)^{1/2}
\]

we determine from these conditions the internal energy \( E_{ig} \) of the ignitor and the lower limit \( M_{ig} \) of the ignitor mass (for DT fuel: \( \rho_f^0 = 0.2 \text{ g/cm}^3, \rho_{f(c)}^0 = 4 \times 10^{10} \text{ erg/cm}^3) :

\[
\begin{align*}
E_{ig} &= E_s \left(\frac{E_{ig}}{E_s}\right)^{7/8}, E_s = 5.6 \times 10^{-2} \left[\frac{M_s^{1/6} M_f^{2/3} (1 + m) T_{ig}^{3/2}}{k \alpha q^{7/3} (\sigma \nu)^{3/2} (1 - k \alpha)^{3/2}}\right]^{8/3}, \\
M_{ig} &\geq 3 \times 10^{-8} \left[\frac{M_s^{1/6} (1 + m) T_{ig}^{3/2}}{q^{8/3} (\sigma \nu)^{3/2} (1 - k \alpha)^{3/2}}\right],
\end{align*}
\]

here \( T_{ig} \) (in keV) is the ignitor temperature, \( E_s \) is in J, \( \sigma \nu \) (in cm\(^3\)/sec) is the rate of the DT reaction; \( k \alpha \) is the fraction of the energy that the \( \alpha \) particles transfer to the compressed part of the thermonuclear matter [4]; \( m = M_q/M_s \).

3. Thermonuclear Gain

The time of inertial containment of the hot target is:

\[
\tau \simeq \left(\frac{3M_f}{4\pi \delta_f \rho_f^0}\right)^{1/3} \left(\frac{M_s}{2E_c}\right)^{1/2}
\]

\[
\text{397}
\]