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EFFECT BY RADIATIVE ENERGY TRANSPORT IN PUSher LAYER AND TRANSPORT PROPERTY OF FUEL ON NONUNIFORM IMPLOSION OF TARGET IRRADIATED BY ION BEAM

K. NIU and T. AOKI

Department of Energy Sciences, the Graduate School at Nagatsuta, Tokyo Institute of Technology, Midori-Ku, Yokohama 227, Japan

Résumé - La compressibilité du combustible dépend fortement de son équation d'état. Les effets de nonuniformité peuvent abaisser fortement le taux de compression. Le transport d'énergie radiative dans la couche où s'effectue l'essentiel du ralentissement, homogénéise les nonuniformités de pression, lorsque la température de la couche considérée dépasse 1 keV, et que l'irradiance du pilote est supérieure à $10^5$ W/cm².

Abstract - In order to obtain a high pressure to compress DT fuel in target for ICF, momenta of pusher and fuel itself are converted to impulse. Compressibility of fuel depends strongly on its equation of state. Target is usually not illuminated by energy driver in spherically symmetric way. Nonuniform implosion decreases severely the rate of fuel compression. Radiative energy transport in pusher layer homogenizes profile of nonuniform pressure which is originated by a nonuniform deposition of driver energy, if the pusher temperature exceeds 1 keV, so that the driver intensity exceeds $10^5$ W/cm². With lower driver intensity, effects of nonuniform pusher pressure must be decreased by the target structure.

1 - INTRODUCTION

In order to extract practical amount of fusion energy from deuterium tritium (DT) fuel in target for inertial confinement fusion (ICF), mass of DT fuel is required to be about 20 mg, and fuel is compressed to more than 1000 times the solid density in order that the fusion parameter $\rho R$ exceeds 4 g/cm² and fuel is heated to more than ion temperature of $T=4$ keV. To compress fuel to such a high density is one of the most difficult subjects to be realized in ICF, and the fuel pressure must reach at least $p=10^{12}$ Pa. This high pressure at the central part of fuel can be realized by compression of fuel in supersonic converging nozzle. Equations of state for ion and electron (especially degeneracy of electron) will affect much fuel compression. Section 2 is devoted to describe these phenomena.

Pusher pressure becomes inhomogeneous owing to the finite number of driver beams, fluctuation of beam energy among beam modules, inhomogeneous distribution of intensity in one beam, instability or nonlinearity of beam-plasma interaction and so on. Since nonuniform implosion of fuel is caused by nonuniform pusher pressure and it decreases significantly fuel compression, it is required to keep nonuniformity of pusher pressure less than 2%. Radiative energy transport in pusher layer will play a role on smoothing pressure. In the case of indirect drive of laser fusion by using a short pulse, a laser intensity of more than $10^{15}$ W/cm² leads us to a high pusher temperature of order of 1 keV. Under this circumstance, pusher pressure can be homogenized by radiative energy transfer. In the case of particle beam fusion, such a high intensity of energy driver can not be expected to be realized, and fluctuation of beam-energy deposition in pusher layer may happen to exceed 10%. Under these circumstances, uniform implosion is expected to be performed by improving target structure.
Figure 1 shows the phase diagram of DT fuel in n-T plane \( T \), where \( n \) is the number density and \( T \) is the temperature. In the figure, the point \( P \) refers the starting condition of fuel for ICF and the point \( Q \) refers the final condition. At the point \( P \), fuel is in solid state. After acceleration of fuel by pusher pressure, fuel temperature increases and fuel becomes plasma. When plasma density is high and plasma temperature is low, electron in the plasma is degenerated. Figure 2 shows plasma pressure \( p \) versus plasma temperature \( T \) for the solid density of \( \rho = 1.9 \times 10^{12} \) kg/m\(^3 \). Under the temperature \( T = 10^5 \) K, plasma pressure becomes constant because of electron degeneracy. Electron degeneracy decreases fuel compression.

At the final stage of implosion, plasma density is requested to be more than 1000 times the solid density and plasma temperature is more than 4 keV. Then fuel pressure reaches at least \( p = 10^{15} \) Pa. On the other hand, if intensity of \( 10^{15} \) W/cm\(^2 \) of driver beam are launched to a target, and deposits its energy in pusher layer, pusher pressure increases rapidly to \( 10^{20} \) Pa. This high pressure accelerates fuel (whose mass is 20 mg) toward target center with the acceleration of \( a = 7 \times 10^6 \) m/s\(^2 \) and implosion velocity arrives at \( u = 3 \times 10^7 \) m/s after 5 ns (4.5 \times 10^{-10} \) mm transition).

If we consider that the fuel with the implosion velocity of \( u = 3 \times 10^7 \) m/s is an ideal-gas of the number density of \( n = 4.5 \times 10^{20} \) m\(^3 \), the Mach number of fuel is 38.5. In the real situation, electron in the fuel plasma is degenerated. If electron degeneracy is taken into account, the fuel velocity of \( 3 \times 10^5 \) m/s corresponds to the Mach number of \( 385 \).

Figure 3 shows a part of target. Fuel motion corresponds to supersonic flow in a converging nozzle /3/. The density \( \rho \) at the sonic section is related to the Mach number \( M_0 \) through

\[ \rho / \rho_0 = [2/(\gamma + 1)(1 + (\gamma - 1)M_0^2/2)]^{1/(\gamma - 1)} \]

For \( \rho_0 = 1.9 \times 10^{12} \) kg/m\(^3 \) and \( M_0 = 385 \) at \( r = 3 \times 10^{-3} \) m, \( \rho \) becomes \( \rho = 7.13 \times 10^5 \) kg/m\(^3 \). This value is virtual one.

For degenerated fuel with \( \rho_0 = 1.9 \times 10^{12} \) kg/m\(^3 \) and the initial values of \( M_0 = 38.5 \), \( \rho = 2.69 \rho_0 = 5.12 \times 10^4 \) kg/m\(^3 \) at \( r = 2.57 \times 10^{-4} \) m. If fuel compression is taken into account in subsonic region where flow-locking occurs, the final density of degenerated fuel arrives at \( \rho = 3.51 \times 10^5 \) kg/m\(^3 \) at \( r = 3.0 \times 10^{-5} \) m. Through fuel implosion, first the pusher pressure creates implosion velocity of fuel together with a part of pusher, and next supersonic flow in converging nozzle increases pressure and density of fuel through adiabatic compression due to narrowing cross-sections. This is the mechanism how to create high pressure and hence high density of fuel in ICF in spite of much smaller pusher pressure.
3 - NONUNIFORM ENERGY DEPOSITION IN PUSHER LAYER

When one-shell (three layer) cryogenic hollow target is used for fuel compression, nonuniformity from spherical symmetry causes the decrease in fuel compression. It is required that nonuniformity must be in less than 2% in order not to reduce fuel compression and hence fusion output from a target. One of severe causes for nonuniformity is nonuniform deposition of driver energy in pusher layer. One way to extinguish nonuniformity is to deposit driver energy uniformly in pusher layer. In the case of direct laser fusion, inhomogeneity of energy deposition on target surface seems to exceed 2%.

In the case of light ion beam (LIB) fusion, a theory predicts that fluctuation of energy deposition can be suppressed to 2%, if number of beams is more than 12. In real situation, fluctuation of beam energy among modules or among shots, fluctuation in energy distribution in a beam cross-section, fluctuation of incident angles of beam-particles to target surface including effect of target curvature, fluctuation of radii of propagating beams, fluctuation of target position relative to beam directions and so on produce nonuniform pusher pressure whose nonuniformity will exceed 10%.

Emittance of heavy ion beam (HIB) is very small in comparison with LIB. If the number of beams increases practically to infinity or intensity distribution of one beam is appropriately modified according to the finite number of beams and spherically symmetric irradiation of target is realized, problems with respect to nonuniformity will disappear for HIB fusion. It seems that some structural (or systematic) improvements are required for HIB fusion, if we want to diminish nonuniformity from spherically symmetric irradiation on target.

4 - PRESSURE SMOOTHING BY RADIATIVE ENERGY TRANSFER IN PUSHER LAYER

In the case that temperature of pusher layer is high, there is a possibility that radiation smoothes out the temperature rippling in pusher layer. When beam energy of 6 MJ is deposited in pusher layer during 30ns in target, the pusher temperature increases rapidly and arrives at 94 eV after 5 ns. The corresponding pusher pressure of \(p = 2.7 \times 10^{12}\) Pa (the pusher material is aluminum whose density is \(\rho = 270\) kg/m and average ionization rate is \(\lambda = 4\)) accelerates the fuel (whose mass is 20 mg) toward target center with the acceleration of \(a = 6 \times 10^{13}\) m/s\(^2\). Thus the implosion velocity of fuel arrives at \(u = 3 \times 10^9\) m/s after 5ns (4.5x10\(^{-12}\) m/transition). The work on the fuel done by the pusher pressure per second is \(2.5 \times 10^9\) J and balances with beam-energy deposition in the pusher layer. Thus the pusher temperature is saturated at about \(T = 100\) eV, 5 ns after start of beam irradiation. With the pusher temperature of 100 eV, the radiation energy density in the pusher layer is much smaller than the thermal energy. According to a simulation result, radiation energy density is of \(3 \times 10^{-4}\) times less than the deposited energy of beam at the central pusher region (in the case that atomic number of pusher material is \(Z = 12\) and temperature \(T = 40\) eV) and of \(2 \times 10^{-3}\) times less (for \(Z = 40, T = 40\) eV). Surely radiation energy density increases with atomic number \(Z\) of pusher material, but it is negligibly small to smooth out temperature inhomogeneity in pusher layer when \(T = 100\) eV. When pusher temperature reaches 1 keV, the radiation energy density becomes comparable to the thermal energy and we can expect that temperature smoothing occurs by radiation. The intensity of driver beam is then requested to be \(2 \times 10^{-7}\) W, which is satisfied by the beam total energy of \(E_b = 10\) MJ and the pulse width of \(t = 5\) ns. In the case of glass laser, the intensity of \(2 \times 10^{10}\) W will be reached, if \(E_b = 10\) MJ can be realized. In the case of LIB, to reach the condition of \(t = 5\) ns remains undefined.

When driver intensity is very high, shock waves may appear in fuel layer and fuel is heated before compression. To protect such a shock heating, tailored pulse-shape is required for driver beam.

5 - GASS-FILLED TARGET

In order to suppress defect of nonuniform implosion on fuel compression, fuel is expected to have elasticity against nonuniform pusher pressure. Pressure difference in pusher layer, however, is of order of \(10^{11}\) Pa and no real material exists against such a large pressure difference without diminishing implosion velocity. Thicker fuel layer with smaller density or double layers of fuel decreases the defect by nonuniform pusher pressure. A target which is filled with DT gas fuel inside pusher layer is of rather old type contrary to hollow shell target. If the central part of target is void, the target is efficient for implosion, because no resistive force acts for implosion from vacuum. However, the void is filled really with the saturated vapor pressure of \(10^7\) Pa surrounded by solid fuel. Let us consider the case that fuel mass is \(M_D = 21.5\) mg, target-inner-radius is \(r = 5.35\) mm, the initial fuel pressure is \(p = 3.88 \times 10^7\) Pa which is low enough to be compressed. For gas-filled target, the momentum of the pusher layer toward the target center will be changed to impulse to produce high pressure. In the initial stage of implosion of pusher layer, whose material is aluminum, temperature is \(2.02 \times 10^6\) K and implosion velocity is \(3 \times 10^5\) m/s, the initial Mach
number is $M_1=6.99$ at $r=5.35$ mm. In supersonic nozzle (spherical target), the sonic point appears at $r=1.09$ mm where the pusher pressure becomes $p=6.05 \times 10^5$ Pa. On the other hand, the adiabatic compression leads to $p=6.18 \times 10^5$ Pa inside $r=1.09$ mm. This means that fuel can be compressed enough by high pusher pressure which comes from pusher implosion. The fuel in the gaseous state can be compressed by the high pusher pressure under even nonuniform implosion. The essential point is that pusher pressure does not increase under nonuniform implosion. By using gaseous fuel, vital defect caused by nonuniform energy deposition is surely decreased, although fusion output energy from a gas-filled target becomes small in comparison with cryogenic hollow shell target in spherical implosion.

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