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Thermal resonance effect by a strong shock wave in D–T fuel side-on ignition by laser-driven block acceleration

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Research Article

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Abstract

Ignition with the help of a shock wave is performed by the interaction of accelerated plasma block by a petawatt-picosecond (PW-ps) laser, with a solid-state density fuel that it is a new possibility for achieving controlled fusion by inertial confinement. The unexpected production of plasma blocks provides new access to the ignition of solid-state density fuel according to the Chu hydrodynamic model. When the produced plasma block by the PW-ps laser hits the main fuel due to the density differences between the plasma block and the main fuel of the shock wave, this progressive wave increases the density of solidified fuels and reduces the energy of the ignition threshold and increases the flammability. In this study, a new discovery of shock waves has been observed leading to the resonance phenomenon. Nuclear heat shock waves resonance in the side-on ignition of fuel in the internal layer of fuel at $x \neq 0$ appears from the exact solution of the hydrodynamic equations with respect to the density profile. This important finding achieves the required ignition temperature for solid-state fuel deuterium–tritium (D–T) in certain energies, with a significant increase due to the resonance of thermonuclear waves. This discovery will facilitate practical experiments on the ignition of advanced solid-state fuels with the accelerated plasma blocks by a PW-ps laser at certain energies.

Introduction

The flame of thermonuclear waves in plasma has recently attracted much attention in laser ignition. In the interaction of a highly-intensive plasma-laser, the burning process is such a very dense internal region of the deuterium–tritium (D–T) sphere that reaches to the threshold temperature by a strong convergent shock, while the rest of the fuels are heavily compressed and relatively cold. Then, high-energy alpha particles in the center area of the fusion can heat the surrounding (adjacent) cool fuels to generate ignition. This process leads to the formation of a radial wave and can reach the solid condensed fuel to an ignition state (Courant and Friedirchs, 1977).

A thermonuclear reaction in hot and intense plasma will increase the explosion rate and create a shock wave of thermonuclear. An example of the propagation of thermonuclear waves is the shock heating for low-density plasma ($10^{15}\,cm^{-3}$), which was presented by Fuller and Gross based on the Zeldovich–Neumann model (Fuller and Gross, 1968). The model assumes that the reaction wave consists of a dynamic gas shock which follows a nuclear reaction zone and the shock is strong enough to heat up the gas to a thermonuclear temperature. Because of the simple assumption, this model is not directly applicable by laser-plasma. The development of the reaction wave in solid-state density plasma is presented by Chu and Bobin (Chu, 1972). A created shock wave by the interaction of laser with solid fuel can trigger nuclear reactions and the simple burning of fuel (Winterberg, 1968). For ignition, including the additional mechanisms, such as the propagation of the reaction wave, with the release of produced high-energy alpha particles, were necessary that has been investigated by Brueckner and Jorna (1974). Using energy conservation, they showed that, if the temperature is above 15 keV, the emission of the flame is carried out in ultrasonic velocity. However, their simple model does not include the limited effect of the time dependence of the deposition of alpha particles energy in plasma. In other words, they have assumed that the total energy of the produced alpha particles by the reaction is transmitted instantaneously to the fuel, so the effect of heating in the alpha particles is too real. According to their results, when the temperature is above 30 keV, the emission rate at the ignition source is higher than the alpha particle velocity (Brueckner and Jorna, 1974).

Nozaki and Nishihara (1977) investigated the thermonuclear reaction waves in dense plasma. By use of a decreased decomposition method, they showed that a thermonuclear reaction wave is a weak shock wave, and that the front structure is determined by the propagation of alpha particles instead of electron thermal conduction. In fact, the limited effect of the time

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dependence of the deposition of the alpha particles energy which leads to a deceleration was rejected (Nozaki and Nishihara, 1977).

The structure of stable plasma shock waves has been studied by many researchers. This issue has been examined by Chu and Gross (1969). In contrast to the shock of natural gases, the plasma shock has a multilayer structure. The acceleration of such a shock depends on the mechanism of energy input and energy transfer (Hicks *et al*., 2012).

In order to obtain a high gain, side-on ignition was proposed by Chu and Bobin in accordance with hydrodynamic theory (Bobin, 1974). The ignition of solid fuel D–T with high-energy flux density was possible at 4.3×10^{12} J/M^2, which was impossible at that time. Electron beams with 5 MeV energy were studied in the ignition scheme by Nuckolls and Wood. In their scheme, the very intense relativistic electron beams were generated by petawatt-picosecond (PW-ps) laser pulses for controlled (Nuckolls and Wood, 2002). In this scheme, the fusion gain of big mass ignition of the very dense D–T fuel was up to 10^4. However, this ignition does not work with a single shot because it requires two lasers with different pulse lengths: produced electron beams by laser PW with a shorter pulse length and pressed plasma by a laser with a longer pulse length. Here, an important point is that both plasma-block ignition and fast-ion ignition are both recognized as indirect drive ICF (inertial confinement fusion), based on which the PW-ps laser is utilized in both. However, there are significant differences between these two methods due to the laser contrast. In the plasma-block ignition (Hora et al., 2008), due to the very high contrast ratio of PW-ps laser pulses, unlike the fast-ion ignition (Roth *et al*., 2001), the plasma-block acceleration ions will not have the relativistic effects. Because of the nonlinear (ponderomotive) force of laser applied on the target, the plasma block will be accelerated. Moreover, as the accelerated plasma block by laser collides with the main fuel to perform the fusion reaction, as compared with the fast-ion ignition that a relativistic beam of accelerated ions collides with the fuel, the shock waves are generated that will improve the ignition process. By the accelerated plasma block with a single-shot laser driven (PW-ps), the fusion gain will be increased. This laser pulse may produce accelerated ions in a quasi-neutral plasma block by introducing nonlinear (ponderomotive) force (Badziak *et al*., 1999; Hora *et al*., 2007). An unusual discovery was observed in the interaction of the PW-ps laser with plasma. This abnormal discovery led to the production of an accelerated laser plasma block (Hora *et al*., 2008) containing ions with a current density of 10^{11} A/cm^2 and an energy flux density of 4×10^4 Am/cm^2. The accelerated laser plasma block hits the main fuel and this plasma block can cause a quick ignition of the D–T fuel. Ignition is developed and transmitted by heat transfer by electrons and ions throughout the main fuel. The reason for the acceleration of the plasma block by the laser is the insertion of a nonlinear (ponderomotive) force from the laser to the plasma block (Hora, 2007; Malekynia *et al*., 2009, 2010). Zhang *et al.* (1998) achieved an unusual phenomenon in their experiments. Zhang *et al.* observed that all of these unusual observations can be explained by the acceleration of the plasma block by a nonlinear force driven. And this was the basis for the Badziak experiments (Badziak *et al*., 2006). Consequently, the plasma block with a nonlinear force driven leads to the acceleration of very high-energy ions, which accelerates toward the target (solid state density D–T fuel) and creates a thermonuclear reaction.

When the clean laser pulses of the PW-ps is interfaced with a contrast ratio of 10^8 with a thick solid target, the relativistic self-focusing is avoided. The effects of the relativistic self-focusing of the accelerated plasma block have been measured by the Sauerbrey Doppler phenomenon (Sauerbrey, 1996). An unusual phenomenon by using the very clean laser pulse in order to generating of energetic ions was also observed by Zhang *et al.* They observed that only soft X-rays were released, and they did not see any usual hard X-ray emission. The intense emission of hard X-rays was the outcome of the relativistic self-focusing laser pulses. In these Zhang's observations, the following usual relativistic effects were not seen. The outcome of these observations was the creation of plasma block instead of plasma plume (Zhang *et al*., 1998). The result of this phenomenon is that there is no any ignition in plasma block, and the plasma block is regularly accelerated (Lalousis and Hora, 1983). Badziak *et al.* (2006) observed that when the ps laser pulse radiates to the copper target, a 0.5 MeV ion is generated instead of the 22 MeV ion emissions. In addition, the number of ions is independent of the power of the laser. In fact, this plasma block was approved by the laboratory. Laser pulses of PW-ps generated the neutral space plasma block with ionic direct current density higher than 10^{14} A/M^2, including high-energy ions. The plasma block can interact with the objective of solid-state density, and this interaction may result in increased fusion energy and high gain. We use the Chu and Bobin description for solid fuel density. The plasma block hits the main fuel and creates a flash point. Then, the transfer of thermal flux through ions and electrons will expand the thermonuclear reaction to one side of the fuel and its depth (Malekynia and Razavipour, 2012). Mathematically, the emission of ignition flames in the depth of D–T fuel was studied by considering the density profile for ignition in the $x \neq 0$ layer (Malekynia and Razavipour, 2012). In the analysis of data in this study, a new discovery of shock waves leads to the resonance phenomenon. Thermonuclear shock waves resonance in the fuel ignition with the collision of the accelerated plasma block by the PW-ps laser in the internal fuel layer at $x \neq 0$ appears by including the x dependence of the density with the exact solution of the hydrodynamic equations. Therefore, solid-state fuel ignition of D–T can be achieved in certain energies, which will result in a significant increase in gain in these particular energies due to the resonance of thermonuclear waves. In this study, the stages of propagation of thermonuclear shock waves are considered by various energy processes such as alpha particle propagation, shock heating, electron heat conduction, expansion velocity, and bremsstrahlung. Using shock waves is the key to reach the high required density for ICF purposes. Therefore, the resonance of thermonuclear waves in the ICF is very important. Therefore, the propagation of ignition and resonance with the inclusion of thermal shock waves can be calculated by the hydrodynamic equations (continuity equation, density profile, velocity equation, reaction rate, ion motion equation, and electron and ion equation). With the expansion and release of solid-state of D–T fuel, the waves are intensively stimulated, and the energy transmitted by the electrostatic waves is transmitted to the plasma waves. Because these waves are being depleted, energy ultimately converts to thermal energy and resonance with thermonuclear waves. Therefore, by absorbing certain energies, the plasma will heavily hot and the energy gain will increase considerably.

Hydrodynamic calculations of solid-state fuel ignition in the internal layers

According to the Chu theory (Chu, 1972), when the laser light concentrates on a solid-state nuclear fuel, the laser beam is

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absorbed and causes a reaction in a region. By mechanisms, such as electron-induced thermal conduction, electron-ion equilibrium, alpha-particle stopping power, bremsstrahlung, and expansion, thermonuclear reaction waves propagate in solid-state density or in other words, ignition develops and propagates in a solid-state density fuel.

This theory (the side-on ignition of solid-state density) was presented by the time when a volume ignition model appeared to be a problem from a practical point of view because densities of about 100,000 times of the solid-state density were needed; a uniform high-power laser with high efficiency at the time was a major problem. To fuse, the temperature of the electrons is increased by the interaction of the laser pulse directly with the main fuel. Through thermal conduction, the temperature of the ions also rises and, by increasing the temperature of the ions, the ignition develops and propagates in the whole fuel. But at least the necessary energy to ignite the main fuel was inaccessible at that time. Today, it is available with powerful lasers and the formation of a plasma block. Due to the x–t dependence of the electron and ion temperature in the hydrodynamic equations, $T_{e,i}(x.t)$, the differential equations with the energy flux density E* as a parameter for the D–T reaction can be used to analyze the fusion conditions. See the set of Eqs (1)–(19) of Malekynia and Razavipour (2012). In Eqs (4) and (5), respectively, the right-hand sides are related to expansion, thermal conduction, electron and ion balance, and the increased temperature of the generated heat by the fraction of the absorption of the alpha particles by the electron or the ion. The end term ($AT_e^{1/2}$) in the equation of the electron temperature is related to the loss of bremsstrahlung. In this study, E_α is the energy of the alpha particles. The alpha particles energy absorbed by electrons is described by Butler and Buckingham (Ray and Hora, 1976; Hora and Ray, 1978). Then, the alpha particles are assumed to deposit their energy in the plasma. Due to be long of the neutron mean free path which at solid density is about 20 cm, the energy of the neutrons is not assumed to be absorbed by plasma (Chu, 1972).

Therefore, the ignition conditions are obtained in the $x \neq 0$ layers (Malekynia and Razavipour, 2012):

$$W_i + W_e = AT_e^{1/2} + \left(\frac{4}{3}\right) T_e \frac{\partial u}{\partial x} - \left(\frac{2}{3nk_B}\right) \frac{\partial}{\partial x}\left[(K_e + K_i) \frac{\partial T_e}{\partial x} \right] \tag{1}$$

Equation 1 shows energy gain changes. In this equation, it is assumed that the derived energy from the fusion reaction must be at least equal to the loss of bremsstrahlung and cooling due to expansion (Chu, 1972; Malekynia and Razavipour, 2012). It is clear that this equation shows dependence on density, expansion velocity, and electron temperature. An ion temperature with x–t dependence is obtained using the numerical solution of Eq. (1). By applying the expansion velocity of Eqs (16) and (17) of Malekynia and Razavipour (2012), the density profile ρ is achieved [Eq. (18) of Malekynia and Razavipour (2012)], and by replacing $n = \rho/M$ in Eq. (1), the fusion conditions for the layers $x \neq 0$ will be obtained. In Eq. (1), k_B is Boltzmann's constant, T_e is the electron temperature, W_i and W_e are the energy transfer, u is the expansion velocity, $K_{i,e}$ is the thermal conductivity coefficient of an ion or electron, and $m_{i,e}$ is the mass of the ion and electron. For different input energies, this curve is shown in Figures 2 and 3 of Malekynia and Razavipour (2012). The curve of Figure 2 for the input energy is less than $E_t^* = 1.95 \times 10^{15}$ erg/cm^2. They do not have temperature peaks and describe the simple burning of solid fuel. The curves of Figure 3 are related to the input energy over E_t^*. The maximum peak curve temperature indicates solid fuel ignition. By comparing Figures 2 and 3, it can be concluded that the ignition threshold at the depth of D–T plane fuel in the $x \neq 0$ layer is significantly reduced in comparison with the ignition threshold 4.3×10^{15} erg/cm^2 in the $x = 0$ layer for solid fuel. Therefore, the ignition energy flux density E_t^*, for the $x \neq 0$ layer, is reduced by 50% compared with the $x = 0$ layer (Hora *et al*., 2008; Malekynia and Razavipour, 2012).

This reduction in the ignition threshold is an important step in ignition; the plasma block with a nonlinear force driven and it is an advance for ignition with ion beams (Malekynia and Razavipour, 2012). This result increases the self-heating of alpha particles and reduces the loss of bremsstrahlung that is predictable. The ignition time decreases in the depth of the solid fuel as compared to the surface of the fuel (Hora *et al*., 2008; Malekynia *et al*., 2009). So it will increase the gain. It is observed that the temperature threshold of the ignition in the depth of solid plane fuel is $T^* = 3.966$ keV, which is lower than the temperature threshold of ignition at the fuel surface (6.9 keV) (Malekynia *et al*., 2010).

Calculations of the collision region of the plasma block and the main fuel with solid-state density

Figure 1 illustrates the acceleration of a plasma block by the nonlinear (ponderomotive) laser force toward the main fuel. The plasma block is pointing to the back of the laser that contains high inertia. Thus, it directs another explosive block to the main fuel. In flat geometry as shown, if the thickness of the explosive plasma block, i.e., ΔR, is much smaller than that of R_0–R, the collision transfer time will be very low and negligible. Therefore, the explosive plasma block can be considered so that all contents inside of the plasma block are heated in an instant. It is also assumed that the explosive plasma block does not deform during the motion. Finally, when the plasma block reaches the main fuel, an ionic shock or shock wave occurs (Mohammadian Pourtalari *et al*., 2012).

The explosion is created by the shock wave and increasing both temperature and density in the collision region. After the explosion, the deflagration is propagated. The deflagration propagation model was first proposed by Fauquignon and Floux (Bobin *et al*., 1969). The present approach is slightly different from theirs but follows Fraser method (Fraser, 1960). It is assumed that the movement of the fluid is flat and one-dimensional. The equations for the conservation of mass, conservation of momentum, and conservation of energy describe the hydrodynamic behavior of the fluid:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x} a\rho u^2 + p_x = 0 \tag{3}$$

$$\rho T \frac{\partial S}{\partial t} + \rho u T \frac{\partial S}{\partial x} + \frac{\partial E_{\text{in}}}{\partial x} = 0 \tag{4}$$

where u is the velocity of the particle, P is the pressure, and S represents entropy. The fluid is divided into two parts by a flat

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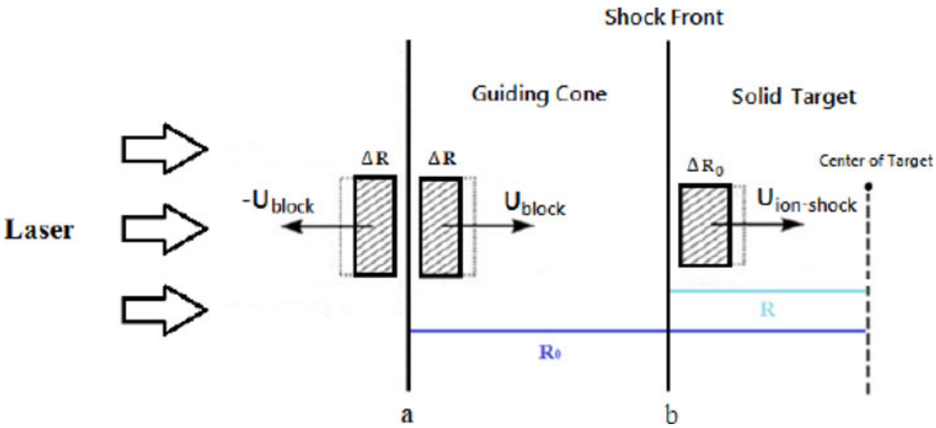

Fig. 1. Accelerated plasma block and the explosion ion collision into the target.

boundary perpendicular to the movement. On the right (i.e., variables having characteristic 1), there is no explosive plasma block landing energy flux, while on the left (i.e., variables having characteristic 2), there is a constant or relatively constant explosive plasma block landing energy flux E_{in}. The flux moves toward the side of the boundary. Then, for the set of Rankine–Hugoniot equations can be written as

$$\rho_1 u_1 = \rho_2 u_2 = J \qquad (u = JV, J < 0) \tag{5}$$

$$Ju_1 + p = Ju_2 + p_2 \tag{6}$$

$$J\left(\frac{1}{2}u_1^2 + \epsilon_1 + p_1 V_1\right) = J\left(\frac{1}{2}u_2^2 + \epsilon_2 + p_2 V_2\right) + E_{in} \tag{7}$$

where J represents mass density, ρ_1 density before the passage of the shock wave, ρ_2 density after the passage of the shock wave, V is the specific volume, and ϵ is the internal energy in thermodynamics.

$$d\epsilon = TdS - pdV \tag{8}$$

Thermal radiation considered negligible in the set of Rankine–Hugoniot equations. Considering Eqs (5)–(7), the following relations are obtained:

$$E_{in} = -J\left[(\epsilon_2 - \epsilon_1) + \frac{1}{2}(p_1 + p_2)(V_2 - V_1)\right] \tag{9}$$

$$E_{in} = -JH_{21} \tag{10}$$

$$H_{21} = 0 \tag{11}$$

Equation 11 is the well-known adiabatic shock equation which is referred to as the Hugoniot curve.

$$\rho_1^2 u_1^2 = J^2 = \frac{(p_2 - p_1)}{(V_1 - V_2)} \tag{12}$$

The thermodynamic variables in both the first and the last conditions must satisfy the requirements for Eqs (5)–(7) and (12). Variations in entropy per unit time and area are equal to:

$$\Delta S = (-J)(S_2 - S_1) - \left(\frac{E_{in}}{T_2}\right) \tag{13}$$

which needs to be positive, i.e., when the flow of material through the boundary changes from state 1 to state 2. The two conditions (1) $\Delta S > 0$ and (2) J must be satisfied so as to obtain the pressure and the density of the boundary from initial conditions and boundary conditions.

The initial conditions, such as ρ_1 & p_1 = constant and ρ_2 & $p_2 = 0$ (solid-state levels are in the first region), correspond to the propagation of deflagration. Nevertheless, as the conditions of region 2 needs to allow the plasma-block energy completely to be absorbed in the boundary, T_2 and p_2 must be relatively high. Therefore, p_2 is much larger than the initial pressure in the solid state. As a result, a shock wave is produced in the boundary due to the difference in pressure and density.

Under high-temperature hydrodynamic conditions, strong shock waves in plasma require consideration of characteristics such as viscosity and thermal conductivity. Energy-related relations are employed to substitute for conductivity coefficients in hydrodynamic equations. During the deflagration propagation process, the dynamic shock wave and the forward deflagration wave are propagated. These waves possess different structures which are investigated independently. If the shock is not sufficiently strong for complete D–T ionization to occur, it would be impossible to obtain a logical physical relation for calculations. Even if the shock wave is sufficiently strong, the state equation and the thermal conductivity equation are not sufficient for accurate analysis of the dense and hot plasma regions. The thermal conductivity and the state equation are employed to express the structure of the deflagration wave (Bobin, 1971).

$$T = \left(\frac{5}{2}(J)\frac{5\gamma - 1}{2(\gamma - 1)}\frac{k}{m_i a}\right)^{2/5}(X_0 - x)^{2/5} \tag{14}$$

$$X_0 = \frac{2}{5|J|}\frac{2(\gamma - 1)}{5\gamma - 1}\frac{m_i a}{k}T_2^{5/2} = \frac{4}{5}\left(\frac{m_i}{k}\right)^{3/2}\frac{\gamma - 1}{5\gamma - 1}a\frac{T_2^2}{\rho_{block}} \tag{15}$$

Relation 14 expresses a thermal profile for deflagration. The specific length X_0 defines the thickness of the deflagration region, γ is the coefficient for atomicity, ρ_{block} is the plasma-block density, and T_2 represents the temperature for plasma.

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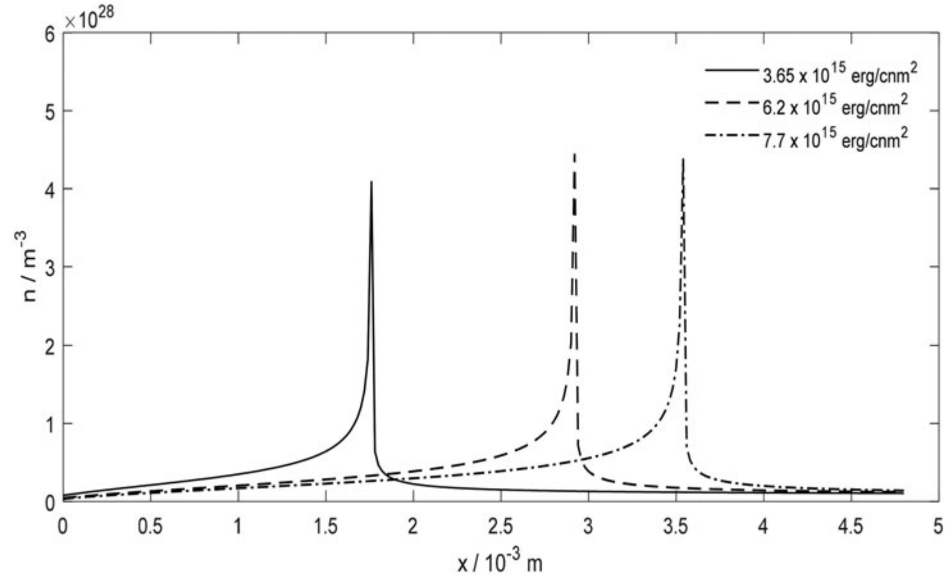

Fig. 2. Density of the ignition region in terms of initial characteristic of the thermal wave.

To calculate density, one can employ Eq. (6) for the conservation of momentum (Bobin, 1971).

$$\left(\frac{J^2}{\rho}\right) + \rho\left(\frac{kT}{m_i}\right) = JC_1 \tag{16}$$

$$\rho = -C_1 + C_1^2 - 4\left(\frac{kT}{m_i}\right)\left(\frac{Jm_i}{2kT}\right) = \rho_{\text{block}}\left\{T_2 + [T_2(T_2 - T)]^{1/2}\right\}/T \tag{17}$$

$$C_1 = 2u = \left(\frac{kT}{m}\right)^{1/2} \tag{18}$$

In the case of the two-component plasma, we have:

$$\rho = \rho_{\text{block}}\left\{3T_2 + [T_2(9T_2 - 8T)]^{1/2}\right\}/4T \tag{19}$$

Relation 19 is concerned with the calculation of density in the plasma-block energy placement zone. The density in this zone can be calculated with the reference to data on this zone or the deflagration temperature (Hoffmann *et al*., 2005). Figure 2 depicts a sample of numerical calculations for Relation (19) concerning the deflagration zone density in terms of the initial characteristic of the thermal wave.

The figure shows that at a specific distance, a peak can be observed in the curve whose fact is due to the absorption of plasma-block energy and ignition propagation.

Description of resonance in side-on ignition by plasma block

An important feature of plasma is their ability to convey a collective turbulences or waves, which in the simplest way is the same as the rise and fall in the density of electrons and ions. Understanding the wave phenomenon in ICF is important because the laser light not only interacts directly with plasma's particles but also with plasma's waves (Nozaki and Nishihara, 1977). If the plasma is very turbulent at a very short time, as when the energy is transmitted by the driver, the turbulence is propagated by the speed of sound c_s to the adjacent regions of the plasma (Eliezer and Hora, 1989). Due to the speed of sound $c_s \sim \rho^{1/2}$, turbulences in high density are released faster than the low density. Therefore, if turbulence is released quickly and moves into a high-density region, it results in a shock wave. This shock wave is ultrasonic and is faster than the sound speed in lower density plasma. The famous Mach number M is commonly used to represent a shock wave and is defined as the ratio of the speed of the shock wave v_{shock} to the speed of sound at the front of the plasma front of the shock wave $v_{s.o}$. Given that $M = (v_{\text{shock}}/v_{s.o}) > 1$, because the shock speed is greater than the sound speed, the Mach number is always larger than one. Mathematically, such a shock can essentially appear in the form of turbulence in density, velocity, and temperature in the hydrodynamic equations. In reality, the shock front is not infinitely small, since the effects of thermal conductivity and viscosity to some extent cause it to expand (Eliezer and Hora, 1989). On the threshold of very weak shocks, the propagation of turbulence leads to the propagation of an iso-anthropic sound wave. In ICF, there are very strong shocks. Therefore, in ICF researches with laser pulses, the fusion process will be developed by the help of produced shock waves as much as possible.

The formed plasma by laser interaction with a solid target has a nonhomogeneous density that composed of two high-density and low-density regions. Whenever the light reaches plasma with these characteristics, electrostatic waves are excited when each of the components of the electric field of light is aligned with the direction of the density gradient. In this case, the electric field is near the critical level, and this is where the waves are intensively stimulated. In this way, the energy of the electromagnetic waves is transformed into plasma waves. As these waves are being depleted, energy is eventually converted to thermal energy and so the plasma is heated. The whole process of converting laser energy into plasma heat is referred to as resonance absorption by wave stimulation (Atzeni *et al*., 2014).

Resonance absorption can also be effective for very low electron-ion collision frequencies. Therefore, resonance absorption can affect the bremsstrahlung for high plasma temperatures, low critical

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densities, and short length plasmas. In other words, the resonance absorption of the main absorption process for high wave lengths and high laser intensities is high. The main characteristic of the absorption resonance is that most of the absorbed energy in the plasma is carried by a small fraction of plasma electrons. This means that as a side effect, many unwanted hot electrons have been created that cause the initial heating of the plasma in front of the shock (Atzeni *et al*., 2014). In ignition with the plasma block, these turbulences will be caused by the interaction of the plasma block with the main plane fuel due to the differences in their density. The produced plasma in the original fuel has a non-homogeneous density that composed of two high-density and low-density regions. The created electric field by the double-layer (Eliezer and Hora, 1989) will coincide with the direction of the density gradient and the electrostatic wave of the plasma will be excited and intensely stimulated. Due to the extraordinary damping of these waves, the energy is immediately transferred to the plasma in heat and thus causes the plasma to heat up. This plasma heating by the thermal resonance of the interactions of the plasma block with the main fuel will result in certain input energies that will be effective in facilitating fusion conditions.

Numerical results

Numerical results are obtained by solving Eq. (1). Multiple code sets in MATLAB are utilized to obtain mentioned figures. The basis of calculations is Eq. (1). The electron temperature in Eq. (1) is calculated based on Eq. (4) proposed by Malekynia and Razavipour (2012). For Figures 2 and 3 of Malekynia and Razavipour (2012), by applying the expansion velocity of Eq. (16) and (17) of Malekynia and Razavipour (2012), density profile ρ [Eq. (18) of Malekynia and Razavipour (2012)] and by replacing at $n = \rho/M$ in Eq. (1), the fusion conditions are obtained for the layers $x \neq 0$. Thus, the new figures in this section, the numerical results of the resonance of thermonuclear waves in the depth of D–T fuel are presented by including of Eq. (19). This solution states that at the time of t, the heat is penetrated to the depth x. The difference between this set of computations and previous ones is that the density profile of Eq. (19) of this paper is used in Eq. (1).

Figure 3 shows the resonance of thermonuclear waves in D–T depths, taking into account the x-dependent density, in certain amounts of specific energies. The resulted curves show changes in the maximum ion temperature with respect to the time and depth of the fuel for the ignition condition. As can be seen from Eq. (1), the primary phenomenon, which is characterized by the conduction of electron, also reaches other phenomena. The most important mechanisms in the thermonuclear reaction waves are the conductivity effects, the transition of the temperature of the electron, the expansion velocity, and the bremsstrahlung. The thermal conductivity effect is included. In long periods of time, expansion, effects of speed, and bremsstrahlung are also observed. According to Figure 3, the shock wave, when produced at a certain amount of energy E in a certain boundary region, generated resonances by thermonuclear reaction waves trigger an explosive wave. The structure of an explosive wave is, in fact, the dynamic shock that has a width equal to several free paths, followed by a high-temperature region, which in turn leads to the resonance of thermonuclear waves. The relevant condition in plasma ignition is actually the onset of an explosive wave in the plasma. This wave will be a shock wave of the plasma. When a plasma shock begins in the x-dependent density of fuel, a variety of characteristics like resonances will be appeared. In order to reach the specified temperature of ignition, as well as the resonance of thermonuclear reaction waves at the depth of D–T fuel in the $x \neq 0$ layer, all energy is first transferred to the electrons. The balance is placed on the thermal layer. In this layer, due to the loss of the bremsstrahlung and nuclear reactions, there is no steady state in the plasma shock. The bremsstrahlung decreases the electron temperature. In the steady state, the heating time of the electron thermal layer will be shortened and the duration of the electron-ion balance will be long. An ion shock can actually be seen as a shock wave inside a heated environment. The ions of before shock are heated by electrons through ionic thermal equilibrium. One of the effects shown in Figure 3 is nuclear heating, which influences the increase in the energy of the wave. On the other hand, the effect of this heating on the wave profile depends on the location of the heating and also whether the electrons or ions prefer heat. In Eq. (1), most of the generated energy by electrons is absorbed. Due to the high conductivity of the electrons, this heating leads to an overall increase in the temperature of the electron thermal layer. In fact, with electron-ion equilibrium, the upstream ions of the shock heat up. Figure 3 is depicted for a variety of input energies. The unusual sudden peaks in Figure 3 are the resonances that produced by thermonuclear waves. In fact, electrons emit these energies by conduction. Therefore, the heating of ions leads to thermonuclear reaction waves and creates resonances. So resonance is generated in certain energies. It can be concluded that shock waves are generated in these energies. Therefore, in certain energies, the ignition temperature increases suddenly, and in these energies, the plasma is heated and energy is transferred to the plasma. For the initial input energy in Figure 3, ion temperature gradually increases and then decreases. In fact, it corresponds to the ignition state. This result is very important in ICF ignition. Therefore, the high required temperatures for thermonuclear reactions must be achieved through the absorption of released nuclear energy. The energy dissipation mechanisms are required to achieve a self-sustained fusion explosion that should include expansion velocity, bremsstrahlung, and conduction effects.

In Figure 4, for better display resonance energies only the x-dependent of the maximum temperature of the plasma ions is plotted for different energy values. The resulting curves show the maximum ion temperature changes in the fuel depth for ignition conditions. The numbers on the peaks are the same as the input energies of accelerated plasma block ions by the PW-ps laser. Therefore, the ignition criterion is characterized by an unusual increase in the maximum ion temperature. For example, with 3.65×10^{15}, 6.20×10^{15}, and 7.70×10^{15} erg/cm^2 the input energy of plasma block ions, the unexpected big sudden peaks are observed at plasma temperatures of 28.00, 38.61, and 37.46 keV. These will be the resonances of thermal thermonuclear waves. In fact, in these given energies, the maximum ion temperature will have an unusual sudden increase compared with the rest of the energies. In ignition, the amount of released energy that corresponds to the reaction plasma is very important in determining the ignition energy. In fact, at these temperatures, the thermal shock resonance of the thermonuclear waves happens. So in these energies, the plasma will be very hot. With the plasma heating, the charged particles have a great chance to lift their energy in the region. In fact, with the increase in the temperature of the ions, the energy of the waves also increases. Therefore, the increase in the ignition temperature in certain energies and the heating of the plasma will be an important parameter of ignition. In the

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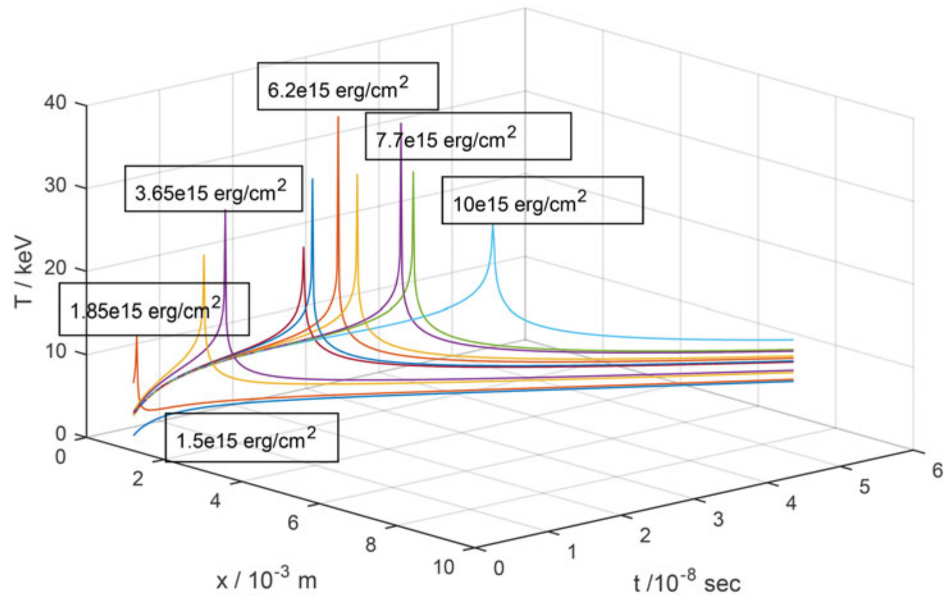

Fig. 3. Resonance of ion temperature changes with input energy (erg/cm^2) as a parameter in the depth of D–T fuel, taking into account the x-dependent density.

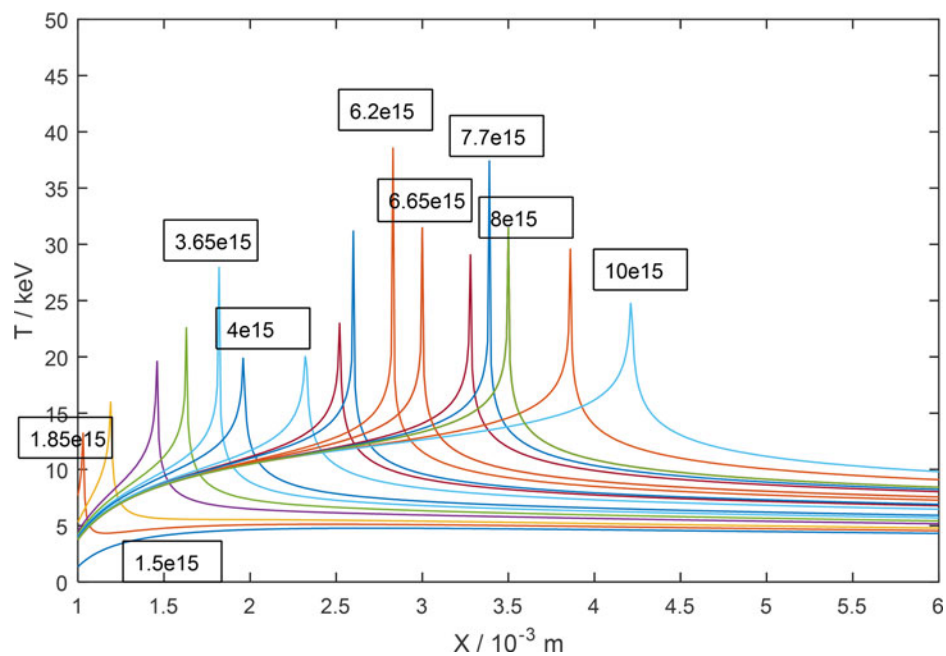

Fig. 4. Resonance of the ion temperature with input energy (erg/cm^2) as a parameter changes in terms of the parameter x (the depth of the D–T plane fuel), taking into account the x-dependent density.

hydrodynamic calculations, the amount of the absorbed nuclear fusion energy by the plasma is equal to the produced energy of the alpha particles in the reaction. For produced resonances, it is observed that the bremsstrahlung is an important mechanism of energy dissipation. The above analysis shows that bremsstrahlung losses and expansion losses are very important. In Eq. (1), the shock wave will be generated by taking into account the xt dependence of density, velocity, and temperature. Thus, by choosing the specific input energy values with the resonance occurrence, the temperature can be greatly increased and the ignition conditions will be improved.

These shock waves are produced due to density discrepancy of the plasma blocks with main solid fuel, which the progressive wave increases the density of the solid-state D-T fuel.

By coupling of the peak points in Figure 4, the curve of maximum changes of the peak temperatures for the input energies is obtained as Figure 5. Figure 5 depicts a sudden increase and decrease so-called resonance at plasma temperature, which is in good agreement with Figure 2. Due to high cost of practical experiments, the computations and computer tests must first be carried out to avoid multiple repetitive tests. Therefore, based on the implemented computations, as shown in Figure 5, it reveals that there will be more profit at the specific energy in the ignition by the plasma block due to the created resonance.

What is certain is that the curves of Figures 2 and 3 of Malekynia and Razavipour (2012) include only an increasing trend, while the obtained curves in Figures 3 and 4, which are especially obvious in Figure 5, include a sudden increasing and decreasing trend, in which the resonance phenomenon is quite clear.

Turbulence is needed to create a shock wave in a fluid environment, and firstly, the turbulence speed must be higher than the

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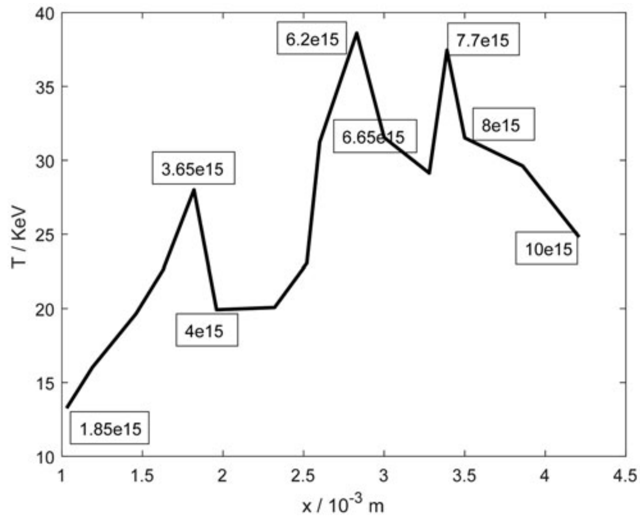

Fig. 5. Resonance of the maximum ion temperature with input energy (erg/cm^2) as a parameter changes in terms of the parameter x (the depth of the D–T plane fuel), taking into account the x-dependent density.

wave velocity. Secondly, it causes nonlinear changes in the environment. The relationship between the densities ratio of before and after the shock-wave propagation from the set of Rankine–Hugoniot equations is (Eliezer and Hora, 1989)

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)p_2 + (\gamma - 1)p_1}{(\gamma - 1)p_2 + (\gamma + 1)p_1} \quad (20)$$

where ρ is density and γ is the specific heat ratio. In Eq. (20), the 1 indexes for the high-flow region and the 2 indexes for the low-flow region. If the difference in the two densities is too high, then there will be a strong shock wave that will increase the threshold temperature of the ignition. The equation can be written more simply:

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)}{(\gamma - 1)} \quad (21)$$

The transmission of a shock wave from solid-state fuel by the collision of the plasma block with the main fuel and the creation of a resonance phenomenon with the increasing density causes the plasma temperature to rise to about 40 keV in the ignition state and changes the ignition conditions.

Conclusion

Thermal shock waves resonance phenomenon in thermonuclear reactions at the depth of D–T fuel, with respect to the x-dependent density, significantly improves ignition conditions. As a result of the creation of the resonance of the shock waves in thermonuclear reactions at the fuel depth in the inner layer $x \neq 0$, will be one of the important and desirable aspects of empirical tests. The resonance properties of thermonuclear waves depend on processes, such as shock heating, electron heating conduction, electron temperature transitions, expansion velocity, density profiles, and bremsstrahlung, so that the temperature rises to about 40 keV. Due to the use of PW-ps does not produce any pre-pulses, and with the direct radiation of laser beams to the very target, plasma blocks are produced, which include high-energy ions with a density of 10^{14} A/M^2. By interacting this plasma block with the main fuel due to the density discrepancy between the plasma block and the main fuel, shock waves are created in the depth of fuel, which increases the gain of the ignition. The results of numerical calculations show that with the interaction of plasma block and main solid fuel, the strong shock wave propagates at certain input energies. The shock waves cause the resonance phenomenon. The ignition temperature suddenly increases unusually. The plasma will become warmer than usual, which will greatly improve the performance of nuclear fusion experiments and obtain a favorable result.

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