In depth fusion flame spreading with a deuterium–tritium plane fuel density profile for plasma block ignition*

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Solid-state fuel ignition was given by Chu and Bobin according to the hydrodynamic theory at $x = 0$ qualitatively. A high threshold energy flux density, i.e., $E^* = 4.3 \times 10^{12}$ J/m^2, has been reached. Recently, fast ignition by employing clean petawatt–picosecond laser pulses was performed. The anomalous phenomena were observed to be based on suppression of prepulses. The accelerated plasma block was used to ignite deuterium–tritium fuel at solid-state density. The detailed analysis of the thermonuclear wave propagation was investigated. Also the fusion conditions at $x \neq 0$ layers were clarified by exactly solving hydrodynamic equations for plasma block ignition. In this paper, the applied physical mechanisms are determined for nonlinear force laser driven plasma blocks, thermonuclear reaction, heat transfer, electron–ion equilibration, stopping power of alpha particles, bremsstrahlung, expansion, density dependence, and fluid dynamics. New ignition conditions may be obtained by using temperature equations, including the density profile that is obtained by the continuity equation and expansion velocity. The density is only a function of x and independent of time. The ignition energy flux density, E_t^*, for the $x \neq 0$ layers is 1.95×10^{12} J/m^2. Thus threshold ignition energy in comparison with that at $x = 0$ layers would be reduced to less than 50 percent.

Keywords: plasma block, solid-state fuel, ignition, expansion velocity

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1. Introduction

In order to obtain high gain, the side-on ignition idea was proposed by Chu[1] and Bobin[2] according to the hydrodynamic theory. The ignition of solid deuterium–tritium (DT) fuel has since arrived at a very high energy flux density, i.e., $E^* = 4.3 \times 10^{12}$ J/m^2 that was impossible previously. The 5-MeV electron beams in the ignition scheme given by Nuckolls and Wood[3] could provide fusion gain by petawatt–picosecond (PW-ps) laser pulse-driven electron beams for controlled fusion. In this scheme a large mass of low density compressed DT fuel produced the fusion gain above 10^4.[3] However, this ignition is not workable with a single shot because the generated electron beams from a petawatt (PW) laser should interact with highly compressed plasma by using another laser with a longer during pulse. The alternative scheme PW-ps laser driven plasma blocks, a single shot, may lead to high fusion gain. These laser pulses may lay a basis of a similar scheme for laser-driven ion beams in quasineutral plasmas by using nonlinear force-driven directed plasma blocks.[4] The plasma block, the anomalous phenomenon, was observed in the experiments by Sauerbrey,[5] Zhang *et al.*,[6] Badziak *et al.*,[7] and Badziak.[8] First, when the clean PW-ps laser pulses with 10^8 contrast ratio interact with a thick solid target, the relativistic self-focusing is avoided. The acceleration of a plasma block from Doppler shift has been measured by Sauerbrey.[5] The second anomalous phenomenon with a clean laser pulse irradiating the target was observed by Zhang *et al.*[6] Soft X-rays were emitted; there was none of the usual hard X-ray emission. The intense hard X-ray emission was the result of the relativistic self-focusing of laser pulses. The subsequent usual relativistic effects were not observed in Zhang *et al.*'s experiment.[6] The result of this phenomenon is the generation of a plasma block without building-up a plasma plume. The third observation was done by Badziak *et al.*[7] when the clean ps laser pulses irradiated copper targets, instead of 22-MeV ion emission, 0.5-MeV ions were created. Furthermore, the number of ions was independent of laser

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power. This directed quasi-neutral plasma block was confirmed experimentally.[8] The PW-ps laser pulses produced the space charge neutral plasma block with a directed ion current density above 10^{14} A/m^2 composed of highly energetic ions.[4]

An accelerated skin layer may be used in laser-driven fusion experiments. The plasma block can interact with a solid-state density target and may lead to intense fusion energy and high gain. To ignite solid-state density fuel we use the evaluations given by Chu[1] and Bobin,[2] when a laser pulse is driven on solid-state DT fuel; the laser pulse is absorbed in a thin layer (near cutoff density). Then, the propagating thermal flux yields the thermonuclear reactions on one side of the fuel. In plasma block ignition, instead of the laser interacting, the accelerated plasma block collides with the solid fuel and the input energy goes deep inside it. The propagation of thermonuclear waves in the solid-state fuel is similar to that described theoretically by Chu[1] and Bobin.[2] As a physical phenomenon, a thermonuclear reaction wave propagates. In other words, the fusion flame spreads in solid-state DT fuel.

The fusion flame propagation can be described by the system of hydrodynamic equations: the continuity equation, reaction rate, the equation of motion, the ion temperature equation, and the electron temperature equation. These equations describe the thermonuclear wave propagation.

In this paper, detailed analysis of the thermonuclear wave propagation is performed by using a numerical technique, with the new fusion conditions at $x \neq 0$ layers considered. By including the expansion velocity in the continuous equation, the density profile is obtained. Due to the importance of density in the Lawson criterion, the dependence of density on t and x is considered. Also, the hydrodynamic equations depend on density. Therefore, this dependence changes the fusion conditions. Finally, the threshold ignition energy will be obtained.

2. Hydrodynamic evaluation

Due to the dependence of hydrodynamic equations on density, the electron and ion temperature equations are derived and the electron temperature, $T_e\,(x,t)$, with the energy flux density, E^*, serving as a parameter for the DT reaction can be used for the initial analysis of fusion conditions. Fusion reactions are based on energetic ions with heat conduction mechanism, hence, the electron energy is transferred to ions.

The equations of continuity and reaction rate for the DT reaction ($\mathrm{D} + \mathrm{T} \rightarrow \alpha + \mathrm{n}$) are defined as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0, \tag{1}$$

$$\frac{\partial Y}{\partial t} + u\frac{\partial Y}{\partial x} = W, \tag{2}$$

where ρ, u, and Y are the mass density, the mass velocity, and the fraction of material burned, respectively. It is clear that Eq. (1) is the same as the mass conservation equation, due to the small percentage ($\sim 0.35\%$) of mass transformed into energy. The reaction rate function W is defined as

$$W = \frac{n}{2}(1-Y)^2\langle\sigma\upsilon\rangle, \tag{3}$$

where n is the density of the ions and $\langle\sigma\upsilon\rangle$ is averaged reactivity. The electron and ion temperature equation are derived by two-fluid momentum equations for electrons and ions in the absence of magnetic field as[1,9]

$$\begin{aligned}&\frac{\partial T_\mathrm{e}}{\partial t} + u\frac{\partial T_\mathrm{e}}{\partial x}\\ &= -\left(\frac{2}{3}\right)T_\mathrm{e}\frac{\partial u}{\partial x} + \left(\frac{2}{3nk_\mathrm{B}}\right)\frac{\partial}{\partial x}\left(K_\mathrm{e}\frac{\partial T_\mathrm{e}}{\partial x}\right)\\ &\quad + \frac{(T_\mathrm{i}-T_\mathrm{e})}{\tau} + W_\mathrm{e} - AT_\mathrm{e}^{1/2},\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial T_\mathrm{i}}{\partial t} + u\frac{\partial T_\mathrm{i}}{\partial x}\\ &= -\left(\frac{2}{3}\right)T_\mathrm{i}\frac{\partial u}{\partial x} + \left(\frac{2}{3nk_\mathrm{B}}\right)\frac{\partial}{\partial x}\left(K_\mathrm{i}\frac{\partial T_\mathrm{i}}{\partial x}\right)\\ &\quad + \frac{(T_\mathrm{e}-T_\mathrm{i})}{\tau} + W_\mathrm{i},\end{aligned} \tag{5}$$

where k_B is Boltzmann's coefficient and included on the right-hand side are the pressure, conductivity, equilibration terms, and thermonuclear energy generation. $AT_\mathrm{e}^{1/2}$ is the bremsstrahlung term. The conductivities are given by[1]

$$\begin{aligned}K_\mathrm{i,e} &= 1.89 \times \left(\frac{2}{\pi}\right)^{3/2}\\ &\quad \times \left[\left(k_\mathrm{B}T_\mathrm{i,e}\right)^{5/2}k_\mathrm{B}/\left(m_\mathrm{i,e}^{1/2}e^4\ln\Lambda\right)\right],\end{aligned} \tag{6}$$

where $m_\mathrm{i,e}$ is masses of ion and electron and e is the electron charge. The energy transfer terms W_e and W_i functions are related to W by

$$W_\mathrm{i} = \frac{2W}{3k_\mathrm{B}}\left[(1-f)\,E_\alpha\right], \quad W_\mathrm{e} = \frac{2W}{3k_\mathrm{B}}fE_\alpha, \tag{7}$$

where E_α is the alpha particle energy, $E_\alpha = 3.5$ MeV. The function f which is the fraction of alpha particle energy absorbed by the electrons has been given by Butler and Buckingham[10] as follows:

$$f = 32/\left(32 + T_\mathrm{e}\ (\mathrm{keV})\right). \tag{8}$$

For different input energies, the electron temperature can be obtained as a function of x and t by a numerical technique using Eq. (4), which is shown in Fig. 1.

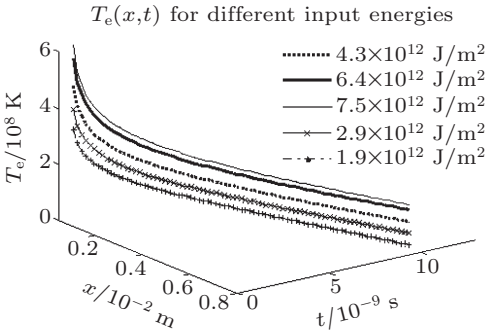


Fig. 1. Characteristics of the electron temperature, $T_e(x,t)$, in the cases of some different values of energy flux density, E^*, for the DT reaction. Temperature on x–t plane for 4.3×10^{12} J/m^2 corresponds to the threshold for ignition nearly identical with the computation of Chu (Ref. [1]).

As expected, the rapid decreasing of electron temperature is related to the first layer of fuel and also to the initial moment ($t = 10^{-9}$ s). Due to the heat conduction mechanism, the maximum value of electron energy is transferred to ions in the initial moment and the ions begin nuclear fusion reactions. The dotted curve shows the threshold for ignition. In the threshold, the bremsstrahlung loss is the same as the plasma heating by the conduction.[1]

3. Expansion velocity

The expansion velocity is obtained by utilizing physical laws after colliding the plasma block with solid fuel. When the ignited solid-state plane fuel expands in the x direction, the decreasing of temperature can be derived according to the first thermodynamics law

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -p\frac{\mathrm{d}V}{\mathrm{d}t} + \frac{\mathrm{d}Q}{\mathrm{d}t}. \tag{9}$$

The first term on the right-hand side of Eq. (9) is related to the work done by pressure. The interaction between laser pulse and fuel is very fast and therefore the second term is neglected.[11,12] Time derivation of fuel volume is written as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}\left(L^2x\right)}{\mathrm{d}t} = L^2\frac{\mathrm{d}x}{\mathrm{d}t}, \tag{10}$$

and using the state equation, pressure is written as

$$p\left(L^2x\right) = \left(N_\mathrm{e} + N_\mathrm{i}\right)k_\mathrm{B}T. \tag{11}$$

The work done by pressure is equal to the internal energy of plasma, i.e.,

$$w = \frac{3}{2}\left(N_\mathrm{e} + N_\mathrm{i}\right)k_\mathrm{B}T, \tag{12}$$

by substituting Eqs. (10), (11), and (12) into Eq. (9), we have

$$T = T_0\left(\frac{x_0}{x}\right)^{2/3}, \tag{13}$$

where T_0 is the initial temperature and is related to the input energy at x_0. As it is clear that the fuel does not ignite completely, thus the average mass $\bar{M}$ is used instead of the total mass M.[11,12] In addition, we use the work–energy theorem

$$p\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}\bar{M}u^2\right), \tag{14}$$

where u is the plasma expansion velocity in the x direction. Using Eqs. (10)–(14) we have

$$\frac{\left(N_\mathrm{e} + N_\mathrm{i}\right)k_\mathrm{B}T_0}{L^2x}\left(\frac{x_0}{x}\right)^{2/3}L^2\mathrm{d}x = \mathrm{d}\left(\frac{1}{2}\bar{M}u^2\right). \tag{15}$$

The average mass can be written as $\bar{M} = m_\mathrm{i}N_\mathrm{i} + m_\mathrm{e}\bar{Z}N_\mathrm{i}$. It can be assumed that $N_\mathrm{i} = N_\mathrm{e} = N$, and $m_\mathrm{e} \ll m_\mathrm{i}$, then $\bar{M} = m_\mathrm{i}N_\mathrm{i} = m_\mathrm{i}N$.[11,12] Finally, the expansion velocity of plane fuel in the x direction is obtained by solving Eq. (15) as follows:

$$u = \left(u_0^2 + \frac{6k_\mathrm{B}T_0}{m_\mathrm{i}}\left[1 - \left(\frac{x_0}{x}\right)^{2/3}\right]\right)^{2/3}, \tag{16}$$

where u_0 is the expansion velocity of fuel at $x = x_0$ that is assumed to be zero.

4. Density profile

The density equation in terms of x is needed to describe the new fusion conditions at $x \neq 0$ layers. The density dependence of the hydrodynamic equation is explained by the following analysis. Using the separation of variable technique yields

$$u\frac{\mathrm{d}\rho(x)}{\mathrm{d}x} + \rho(x)\left(\frac{\mathrm{d}u}{\mathrm{d}x} - k\right) = 0,$$
$$\frac{1}{\rho(t)}\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -k, \tag{17}$$

where k is the constant value. Using Eqs. (16) and (17), the density for $k = 0$ is given by,

$$\rho(x) = \rho_{0x}\exp\left(x^{1/3}\Big/\sqrt{1 - \left(\frac{x_0}{x}\right)^{2/3}}\right). \tag{18}$$

It is clear from Eq. (17) for $k = 0$ that the density is only a function of x and independent of time.

5. Numerical results

Ignition conditions may be obtained by using Eqs. (4) and (5) at $x \neq 0$ layers as follows:

$$W_{\rm i} + W_{\rm e} = AT_{\rm e}^{1/2} + \left(\frac{4}{3}\right) T_{\rm e} \frac{\partial u}{\partial x} - \left(\frac{2}{3nk_{\rm B}}\right) \frac{\partial}{\partial x} \left[(K_{\rm e} + K_{\rm i}) \frac{\partial T_{\rm e}}{\partial x} \right]. \quad (19)$$

This equation explains the energy gain due to the fact that the reabsorption of fusion energy should be equal to the energies for bremsstrahlung loss, expansion, and conduction. It is obvious that this equation depends on density, expansion velocity, and electron temperature. Ion temperatures on x–t curves are obtained by the numerical solution of Eq. (19). For different input energies, these curves are shown in Figs. 2 and 3. The curves in Fig. 2 are related to the input energies less than $E_{\rm t}{}^* = 1.95\times10^{12}$ J/m^2. They do not have temperature peaks and describe the simple burning of the solid fuel. The curves in Fig. 3 are related to the input energies more than $E_{\rm t}{}^*$. The temperature peak of the curve shows the ignition of the solid fuel. By comparing Figs. 2 and 3, one can conclude that $E_{\rm t}{}^*$ is the ignition threshold in the depths of the plane fuel ($x\neq 0$). This threshold is significantly reduced in comparison with ignition threshold 4.3×10^{12} J/m^2 at $x = 0$ for the solid fuel.[1,13,14] Therefore, the ignition energy flux density, $E_{\rm t}^*$, for the $x\neq 0$ layers would be reduced to less than 50 percent in comparison with that for the $x = 0$ layers. This reduction of the ignition threshold is an important step in favour of the nonlinear force-driven plasma block ignition[4] as one of the modifications of fast ignition[15] by ion beams. The higher temperature of peaks (higher gains) and the lower ignition energy threshold of $x\neq 0$ layers for the solid fuel are the consequence of increasing self heating of alpha particles and reducing the bremsstrahlung loss, which is predictable.

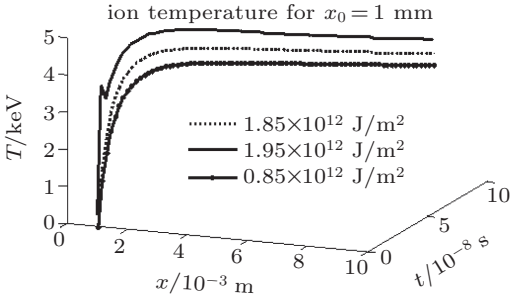


Fig. 2. Characteristics of the ion temperature, $T_{\rm i}\,(x,t)$, in the cases of a few different values of energy flux density, E^*, for the DT reaction. Temperature curve on x–t plane does not have any peak and describes the simple burning of the solid fuel.

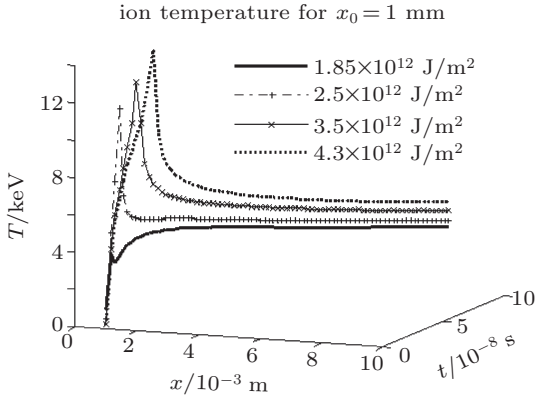


Fig. 3. Characteristics of the ion temperature, $T_{\rm i}\,(x,t)$, in the cases of a few different values of energy flux density, E^*, for the DT reaction. Temperature curves on x–t plane, each with a peak describes the ignition of the solid fuel.

The peak values of curves of Fig. 3 are summarized in Table 1. The ignition time deep inside the solid fuel becomes longer in comparison with that on the surface of the fuel.[1,13,14] Therefore the gain would be increased. It can be seen that the threshold ignition temperature inside the solid-state plane fuel is T^*= 3.966 keV, which is less than the threshold ignition temperature at the surface of the fuel (6.9 keV).[16]

Table 1. Peaks for the different values of energy flux density E^*.

$E^*/10^{12}$ J·m^{-2}	Max ion temperature/keV	x/m	$t/10^{-9}$ s
1.95	3.966	0.0011	1.1
2.1	7.133	0.0011	1.1
2.5	11.75	0.0013	3.1
3.5	13.13	0.0017	7.1
4.3	14.81	0.0021	11.1
6.8	16.77	0.0030	20.1

6. Conclusions

A numerical technique is used to simulate the ignition of solid-state fuel for the exact analysis of fusion conditions and study of ignited plasma dynamics. The numerical results are obtained from the electron and ion temperature equation. Through analyzing the results, it is found that the accelerated plasma block can provide high energy electrons in fuel and it is favourable to the increase of ion temperature due to the heat conduction mechanism. Firstly, the maximum value of electron energy is transferred to ions

rapidly. Secondly, the plasma density is only a function of x and density is independent of time at $x \neq 0$ layers due to the dependence of expansion velocity. It is revealed that the plasma density is very significant for the fusion experiments. Density dependence of the hydrodynamic equation becomes a new condition of fusion for a plasma block ignition scheme. It can also be found that the peaks of ion temperature show ignition of the solid fuel in the fusion flame spreading in the depth of the plane fuel ($x \neq 0$). The threshold ignition energy flux density in the depth is obtained to be $E_{\rm t}^{*} = 1.95 \times 10^{12}$ J/m^2 with 3.966-keV temperature of threshold ignition. These values are less than those under threshold ignition conditions at the fuel surface. Therefore, the obtained higher gains follow the results of alpha particles self-heating with lower loss in depth.

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