The internal propagation of fusion flame with the strong shock of a laser driven plasma block for advanced nuclear fuel ignition*

B. Malekynia† and S. S. Razavipour

Department of Physics, Gachsaran Branch, Islamic Azad University, Gachsaran 75818-63876, *Iran*

(Received 22 October 2012; revised manuscript received 27 December 2012)

An accelerated skin layer may be used to ignite solid state fuels. Detailed analyses were clarified by solving the hydrodynamic equations for nonlinear force driven plasma block ignition. In this paper, the complementary mechanisms are included for the advanced fuel ignition: external factors such as lasers, compression, shock waves, and sparks. The other category is created within the plasma fusion as reheating of an alpha particle, the Bremsstrahlung absorption, expansion, conduction, and shock waves generated by explosions. With the new condition for the control of shock waves, the spherical deuterium–tritium fuel density should be increased to 75 times that of the solid state. The threshold ignition energy flux density for advanced fuel ignition may be obtained using temperature equations, including the ones for the density profile obtained through the continuity equation and the expansion velocity for the $r \neq 0$ layers. These thresholds are significantly reduced in comparison with the ignition thresholds at $x = 0$ for solid advanced fuels. The quantum correction for the collision frequency is applied in the case of the delay in ion heating. Under the shock wave condition, the spherical proton–boron and proton–lithium fuel densities should be increased to densities 120 and 180 times that of the solid state. These plasma compressions are achieved through a longer duration laser pulse or X-ray.

Keywords: block ignition, advanced fuel, quantum correction shock wave

PACS: 52.38.–r, 52.38.Dx, 52.30.Ex, 52.57.–z **DOI:** 10.1088/1674-1056/22/5/055202

1. Introduction

Clean fuel without radioactivity is one of the solutions to the world's energy problem. In addition, the destruction of the ozone layer will be stopped by using nuclear fusion energy. The generation of clean energy will be possible by using p–^{11}B and p–^{7}Li reactions. Due to the low cross section,[1] satisfying the Lawson criterion for the ignition of advanced fuels is not possible by using the previous fusion methods.[2] For ignition, complementary mechanisms are needed. In fast ignition,[3] the compression of fuel and shock waves can help the ignition of the fuel. Non-radioactive fuel will be workable with the development of fast ignition and laser fusion. Complementary mechanisms are divided into two categories. One is using external factors such as lasers, compression, and the Rankyne–Hugonit shock wave. Here the shock wave is generated by impacting the accelerated plasma block with the solid fuel, which follows from the Rankyne–Hugonit simplified analytical model. The other category can be created within the plasma fusion as the reheating of an alpha particle, Bremsstrahlung absorption, expansion, conduction, and shock waves generated by implosions, which are called self similarity. The details of the reheating of an alpha particle and Bremsstrahlung absorption were studied by using the stopping power of the alpha particles according to the collective effect. In view of the collective effect, the energy loss of an energetic alpha particle to plasma was concluded from the alpha particle interaction with electrons and ions. The interaction of an alpha particle with an electron was given by the Rutherford scattering, and the interaction of an alpha particle with an ion was given by the combination of the cross section of Coulomb and elastic nuclear processes. The dependences of the threshold energy and the Bremsstrahlung loss on the collective effect were discovered, see Fig. 2 of Ref. [4]. The expansion and conduction appear in the hydrodynamic equations for plasma block ignition.[5] The shock ignition wave is generated by the assembled fuel ignition from a central hot spot when the massive cryogenic shells are first imploded by direct lasers.[6]

The external factors are easily controlled by laser pulses, size selection, and fuel type. Recently, fast ignition by clean petawatt-picosecond laser pulses was developed. The 5 MeV electron beams in the ignition scheme given by Nuckolls and Wood[7] could provide fusion gain by petawatt-picosecond (PW-ps) laser pulse-driven electron beams for controlled fusion. In that scheme, a large mass of low density compressed DT fuel produced the fusion gain above 10000.[7] That ignition was done with two shots, the electron beams generated by the petawatt laser should interact with the highly compressed plasma by another laser with a longer pulse. The Nuckolls scheme can be used for the fusion of advanced fuels by using a laser fusion plasma block. The compression of plasma by another laser with a longer duration pulse is needed. This compression has two properties. First, the cross sections of nucleons increases and the plasma is warmed. Second, the expansion of the ignited plasma is done slowly. Thus anoma-

*Project supported by the Islamic Azad University of Gachsaran Branch of Iran.

†Corresponding author. E-mail: b_malekynia@iaug.ac.ir

© 2013 Chinese Physical Society and IOP Publishing Ltd

lous observation was made by Badziak.[8] When the clean ps laser pulses irradiated copper targets, instead of the 22 MeV normal ion emission,[8,9] 0.5 MeV ions were produced. This leads to the plasma block ignition driven by a nonlinear force laser. The in-depth plasma block ignition is a new method for the ignition of solid advanced fuels.[5] Due to the low cross section, the ignition of the advanced fuels would be difficult with the plasma block method,[10–12] and controlled complementary mechanisms are needed. Therefore, the fusion conditions are met by the compression of the fuel by another laser with a longer duration pulse and the generated shock wave by impacting the plasma block with the solid fuel. The main fuel density is increased by the shock wave according to the Rankyne–Hugonit simplified analytical model.

In this paper, the radial fusion flame propagation at $r \neq 0$ layers[5] is studied including the generated shock wave by impacting the plasma block with the solid fuel for the advanced fuels, and the fusion conditions of non-radioactive fuels are investigated theoretically. The threshold ignition energy is characterized, and the slower thermalization for ion heating is shown.

2. Radial equations of ignited solid state fuel

The governing equations for the ignition of spherical solid fuels (Eqs. (4), (5), (13), (16), (18) and (19) of Ref. [5]) at $r \neq 0$ layers are written by changing x to r as follows:

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

$$\frac{\partial T_\mathrm{i}}{\partial t} + u\frac{\partial T_\mathrm{i}}{\partial r} = -\left(\frac{2}{3}\right) T_\mathrm{i}\frac{\partial u}{\partial r} + \left(\frac{2}{3nk_\mathrm{B}}\right)\frac{\partial}{\partial r}\left(K_\mathrm{i}\frac{\partial T_\mathrm{i}}{\partial r}\right) + \frac{(T_\mathrm{e}-T_\mathrm{i})}{\tau} + W_\mathrm{i}, \quad (2)$$

where T_e and T_i are the electron and the ion temperatures, u is the mass velocity, k_B is Boltzmann's coefficient, n is the density of the ions, the right-hand side includes the pressure, conductivity, and equilibration terms and the thermonuclear energy generation, $AT_\mathrm{e}^{1/2}$ is the Bremsstrahlung term, $K_\mathrm{i,e}$ is the conductivities of ions and electrons,[13] and m_i is the mass of an ion. The energy transfer terms W_e and W_i are related to the reaction rate W.[13] Equations (1) and (2) are derived by using two-fluid momentum equations for electrons and ions in the absence of a magnetic field.[13,14]

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

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -p\frac{\mathrm{d}V}{\mathrm{d}t} + \frac{\mathrm{d}Q}{\mathrm{d}t}, \quad (3)$$

where p is the pressure, w is the work done, V is the volume, and Q is the heat. The first term on the right-hand side of Eq. (3) is related to the work done by the pressure. The interaction between the laser pulse and fuel is very fast, therefore the second term is neglected.[15,16] The time derivation of the fuel volume is written as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{4}{3}\pi r^3\right) = 4\pi r^2\frac{\mathrm{d}r}{\mathrm{d}t}. \quad (4)$$

By using the state equation , the pressure is written as

$$p\left(\frac{4}{3}\pi r^3\right) = (N_\mathrm{e}+N_\mathrm{i})\,k_\mathrm{B}T. \quad (5)$$

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

$$w = \frac{3}{2}(N_\mathrm{e}+N_\mathrm{i})\,k_\mathrm{B}T. \quad (6)$$

Substituting Eqs. (4)–(6) into Eq. (3), we have

$$T = T_0\left(\frac{r_0}{r}\right)^2, \quad (7)$$

where T_0 is the initial temperature and related to the input energy at r_0. It is clear that the fuel does not ignite completely, thus the average mass $\bar{M}$ is used instead of the total mass M.[15,16] Besides, we use the work–energy theorem

$$p\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}\bar{M}u^2\right), \quad (8)$$

where u is the plasma expansion velocity in the r direction. Using Eqs. (4)–(8), we have

$$\frac{3(N_\mathrm{e}+N_\mathrm{i})\,k_\mathrm{B}T_0}{4\pi r^3}\left(\frac{r_0}{r}\right)^2 4\pi r^2\frac{\mathrm{d}r}{\mathrm{d}t} = \mathrm{d}\left(\frac{1}{2}\bar{M}u^2\right). \quad (9)$$

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 $N_\mathrm{i} = N_\mathrm{e} = N$, $\bar{Z}$ is the mean atomic number, and $m_\mathrm{e} \ll m_\mathrm{i}$, then $\bar{M} = m_\mathrm{i}N_\mathrm{i} = m_\mathrm{i}N$.[15,16] Finally, the expansion velocity of the plane fuel in the x direction is obtained by solving Eq. (9) as follows:

$$u = \left(u_0^2 + \frac{5k_\mathrm{B}T_0(1+\bar{z})}{m_\mathrm{i}}\left[1-\left(\frac{r_0}{r}\right)^2\right]\right)^{1/2}, \quad (10)$$

where u_0 is the expansion velocity of fuel at $r = r_0$ which is assumed to be zero.

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

$$u\frac{\mathrm{d}\rho(r)}{\mathrm{d}r} + \rho(r)\left(\frac{\mathrm{d}u}{\mathrm{d}r} - k\right) = 0, \quad \frac{1}{\rho(t)}\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -k, \quad (11)$$

where k is a constant. By using Eqs. (10) and (11), the density for $k = 0$ is given by

$$\rho(r) = \rho_{\rm or} \tan\left[\sin^{-1}\left(\frac{r}{r_0}\right)\right]. \tag{12}$$

It is clear from Eq. (12) that the density is only a function of r and independent of time for $k = 0$.

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

$$W_{\rm i} + W_{\rm e} = AT_{\rm e}^{1/2} + \left(\frac{4}{3}\right) T_{\rm e} \frac{\partial u}{\partial r} - \left(\frac{2}{3nk_{\rm B}}\right) \frac{\partial}{\partial r}\left[(K_{\rm e} + K_{\rm i}) \frac{\partial T_{\rm e}}{\partial r}\right]. \tag{13}$$

This equation explains the energy gain using the fact that the reabsorption of fusion energy should be equal to the energies of the Bremsstrahlung loss, expansion, and conduction. It is obvious that this equation depends on density, expansion velocity, and electron temperature. The ion temperatures on the r–t curves are obtained by the numerical solution of Eq. (13).

3. Effect of quantum correction on the ignited solid fuel and delayed ion heating

The quantum correction of the collision frequency was reported by Bethe[17] about plasmas. The impact parameter is for the collision of an electron with an ion of charge Z. The question is whether the point mechanical 90° hyperbolic motion of an electron around the ion for calculating the collision frequency is limited after it is in well agreement with the measurements in fully ionized plasmas. The limit should be given if the impact parameter has the value of the de Broglie wavelength, then the wave mechanical scattering has to be used instead of the hyperbola. After this only verbally given remark, the classical collision frequency $\nu_{\rm ec}$ then has to be modified[18] to

$$\nu_{\rm e} = \nu_{\rm ec}, \quad T < T^*, \tag{14}$$

$$\nu_{\rm e} = \nu_{\rm ec} \frac{T}{T^*}, \quad \text{if} \quad T > T^*, \tag{15}$$

where

$$T^* = \frac{4}{3} Z^2 mc^2 \alpha^2, \tag{16}$$

T is the plasma temperature, m is the electron rest mass, c is the speed of light, and the fine structure constant is $\alpha = 2\pi e^2/(hc)$ with the electron charge e and Planck's constant h. In the following, we discuss only p–^{11}B plasmas with $\bar{Z} = 6$ and find $T^* = 1.3284$ keV. The details of the hydrodynamic model are taken with the corrected thermal conductivity of the electrons by the classical value $K_{\rm ec}$

$$K_{\rm e} = K_{\rm ec}, \quad T < T^*, \tag{17}$$

$$K_{\rm e} = K_{\rm ec} \frac{T^*}{T}, \quad \text{if} \quad T > T^*. \tag{18}$$

To use the quantum correction, the thermal conductivity used by Eq. (6) of Ref. [5] has to be changed to[19]

$$K_{\rm e} = \left(\frac{2}{\pi}\right)^{3/2} \frac{20\left[T_{\rm e}^{3/2} \times T^*\right]}{m_{\rm e}^{1/2} e^4 \ln\Lambda}, \tag{19}$$

where $m_{\rm e}$ is the mass of electron, and $\ln\Lambda$ is the usual Spitzer logarithm. The formulation for the temperature according to Chu[13] may be written as follows:

$$\frac{\partial T_{\rm e}}{\partial t} = a \frac{\partial}{\partial r}\left(T_{\rm e}^{3/2} \frac{\partial T_{\rm e}}{\partial r}\right), \tag{20}$$

with $a = K_{\rm e}^{\rm o} \frac{2m_{\rm i}}{3k_{\rm B}\rho}$. Further Chu's Eq. (15) has to be changed to[19]

$$T_{\rm e} = \left(\frac{Q^2}{at}\right)^{2/3} \left[\frac{3}{18}\left(\xi_0^2 - \xi^2\right)\right]^{2/3}, \tag{21}$$

where $\xi = \frac{r}{\left(Q^{3/2}at\right)^{2/7}}$, $Q = E_{\rm in}/\frac{3\rho k_{\rm B}}{2m_{\rm i}}$, and $E_{\rm in}$ is the deposited energy of plasma block.

The results are given in Fig. 3 in diagrams for comparison with the results of Fig. 1 for the plasma of solid state density p–^{11}B, showing the temperature T depending on time t at irradiation energy flux density E^* (erg/cm^2) for cases with and without the quantum correction.

4. Shock wave generation in plasma block ignition leads to fuel compression

Distributions in fluid generate a shock wave. Several shock waves can be studied in the laser driven fusion plasma block ignition. A shock wave is generated inside the exploded fuel.[6] It is self similar and cannot be controlled. Two types of shock waves in the laser driven fusion plasma block ignition can be considered: the generation of shock wave due to the accelerate of plasma block by laser with nonlinear force driven plasma block[4] (see Fig. 5 of Ref. [4]) and the generation of shock wave by impacting the accelerated plasma block with the solid fuel. In this work, the generated shock wave is included by impacting the accelerated plasma block with the solid fuel. The density ratio is calculated by the Rankyne–Hugonit simplified analytical model when the created shock wave propagates in the fuel

$$\frac{\rho}{\rho_0} = \frac{(\gamma-1) + (\gamma+1) P/P_0}{(\gamma+1) + (\gamma-1) P/P_0}, \tag{22}$$

where γ is the adiabatic exponent and is assumed to be $5/3$, ρ_0 and P_0 are the initial values of density and pressure, and ρ and P are the environmental parameters after the propagation of the shock wave. There will be a strong shock wave when the pressure difference is very high, thus $P_0 = 0$, and the density ratio is written as

$$\frac{\rho}{\rho_0} = \frac{(\gamma+1)}{(\gamma-1)}. \tag{23}$$

The shock strong velocity is obtained as follows:

$$v_{\rm s} = \sqrt{\frac{(\gamma+1)P}{2\rho_0}}. \tag{24}$$

The equation of state yields

$$v_{\rm s} = \sqrt{\frac{(\gamma+1)nk_{\rm B}T}{2\rho_0}}, \tag{25}$$

$$v_{\rm s} = \sqrt{\frac{(\gamma+1)nm_{\rm i}k_{\rm B}T}{2\rho_0 m_{\rm i}}}, \tag{26}$$

$$v_{\rm s} = \sqrt{\frac{(\gamma+1)\rho k_{\rm B}T}{2\rho_0 m_{\rm i}}}, \tag{27}$$

$$v_{\rm s} = \sqrt{\frac{(\gamma+1)^2 k_{\rm B}T}{2m_{\rm i}(\gamma-1)}}, \tag{28}$$

where T and n are the temperature and the density of the shocked fluid, respectively. According to the numerical results, the density is increased to four times of the solid state. Finally, the shock strong velocity is given by[20]

$$v_{\rm s} = \sqrt{\frac{6k_{\rm B}T}{m_{\rm i}}}. \tag{29}$$

In the plasma block ignition scheme, due to the density difference between the accelerated plasma block and the solid fuel, the energy of the plasma block is deposited in the fuel and the strong shock is launched into the target. This shock wave changes the fusion conditions.

Another condition of shock ignition is explained by the velocities as follows:

$$v_{\rm s} \gg u. \tag{30}$$

Equation (30) can be applied for the control of shock waves which is possible due to fuel compression; this means the expansion should be done slowly for the compression by the shock wave. Using Eqs. (10) and (30) yields

$$v_{\rm s} \gg \left\{\frac{10}{6}v_{\rm s}^2\left[1-\left(\frac{r_0}{r}\right)^2\right]\right\}^{1/2}, \tag{31}$$

$$r \ll \sqrt{\frac{2}{5}}r_0, \tag{32}$$

where r is the expansion radius and should be followed by Eq. (32). By substituting $r_0 = 1$ mm[5] into Eq. (32), using Eq. (12) and $\rho R \gg 3$ g/cm^2,[21] the spherical DT fuel density should be increased to 75 times that of the solid state. This compression of plasma is done by a laser with a longer duration pulse or X ray (see Fig. 7 of Ref. [8]).

5. Numerical results of the ignition of the advanced fuels in depth

To avoid the radioactive tritium and the dangerous radioactivity created by neutrons, we consider the non-radioactive reactions. p–^{11}B and p–^{7}Li are two important reactions with minimum radioactivity. Using the plasma block ignition scheme for the solid fuel, p–^{11}B and p–^{7}Li ion temperatures on the r–t curves are obtained by the numerical solution of Eq. (13). For different input energies, these curves are shown in Figs. 1 and 2.

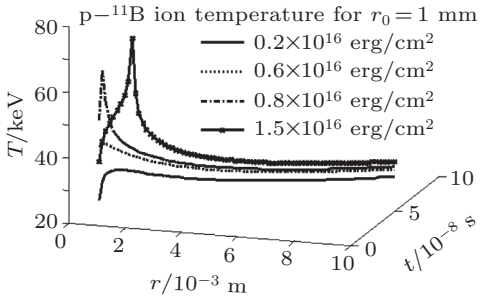


Fig. 1. Characteristics of the ion temperature $T_{\rm i}(r,t)$ with different values of energy flux density E^* for the p–^{11}B reaction.

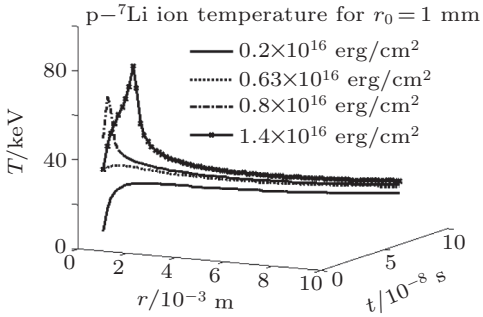


Fig. 2. Characteristics of the ion temperature $T_{\rm i}(r,t)$ with different values of energy flux density E^* for the p–^{7}Li reaction.

The temperature peaks of these curves show the ignition of the solid fuel. In these figures, the dotted curve shows the threshold for ignition where the Bremsstrahlung loss is equal to the heating by the conduction. One can conclude that $E^*_{\rm tp-^{11}B} = 6\times10^{12}$ J/m^2 and $E_{\rm tp-^{7}Li}{}^* = 6.3\times10^{12}$ J/m^2 are the ignition thresholds in the depth of plane fuel ($r \neq 0$) at $T^*_{\rm p-^{11}B} = 44$ keV and $T^*_{\rm p-^{7}Li} = 38$ keV, respectively. These thresholds are significantly reduced in comparison with the ignition thresholds at $x = 0$ for the solid advanced fuels.[12,22] The ignition energy flux density $E_{\rm t}^*$ for the $x=0$ layers is obtained as $E_{\rm tp-^{11}B}{}^* = 1\times10^{13}$ J/m^2 and $E_{\rm tp-^{7}Li}{}^* = 2.5\times10^{13}$ J/m^2 at $T^*_{\rm p-^{11}B} = 87$ keV and $T^*_{\rm p-^{7}Li} = 69$ keV, respectively. This reduction of the ignition threshold is an important step in favor of the ignition of non-radioactive fuels. The higher reduction of $E_{\rm t}^*$ for the p–^{7}Li fuel and the lower ion temperature threshold of $r\neq 0$ layers are the consequence of increasing the self heating of alpha particles and the higher alpha particle energy in comparison with that for the p–^{11}B reaction, which is clear according to nuclear fusion reactions.

The slower thermalization for ion heating is shown in Fig. 3 for the p–^{11}B reaction with the quantum correction for $E_{\rm tp-^{11}B}{}^* = 0.2\times10^{12}$ J/m^2, 1.5×10^{12} J/m^2, and

2.5×10^{12} J/m^2 and without the quantum correction for $E_{\mathrm{tp}-^{11}\mathrm{B}}{}^{*}=0.6\times10^{12}$ J/m^2 and 1.7×10^{12} J/m^2. These results show that the delay of ion heating is important for the ignition of non-radioactive solid fuels at $r\neq0$ layers and the time is shifted from 10^{-8} s to 10^{-7} s.

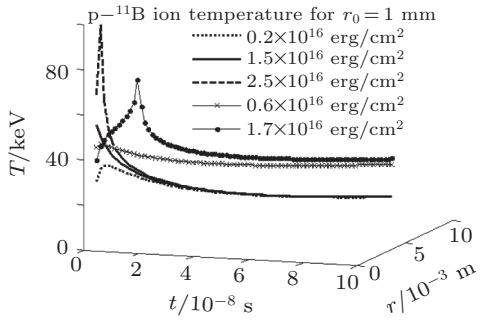


Fig. 3. Characteristics of the ion temperature $T_{\mathrm{i}}(r,t)$ with different values of energy flux density E^* for the p–^{11}B reaction with quantum correction for $E_{\mathrm{tp}-^{11}\mathrm{B}}{}^{*}=0.2\times10^{12}$ J/m^2 and without the quantum correction for $E_{\mathrm{tp}-^{11}\mathrm{B}}{}^{*}=0.6\times10^{12}$ J/m^2 and 1.7×10^{12} J/m^2.

By substituting $r_0=1$ mm[5] into Eq. (32), using Eq. (12) and $\rho R\gg30$ g/cm^2,[21] the spherical p–^{11}B and p–^{7}Li fuel densities should be increased to 120 and 180 times of the solid state, respectively. These compressions of plasmas are done by another laser with a longer duration pulse or X ray.

The reactivity of fusion fuels is investigated by parameter ρR curves. It is summarized in Fig. 4.

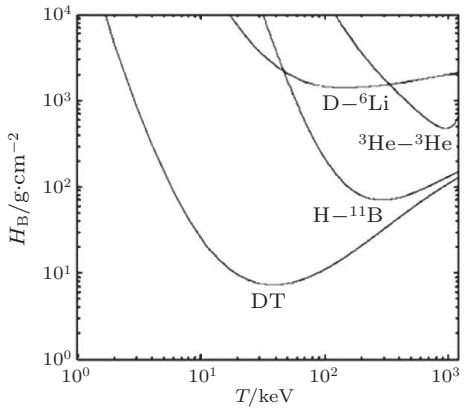


Fig. 4. Characteristics of the reactivity of fusion fuels, where H_{B} is the minimum value of the ρR parameter.[23]

It can be seen that the minimum ρR ($\rho R\gg H_{\mathrm{B}}$) for the DT fuel is 6 g/cm^2 and that for p–^{11}B is 60 g/cm^2. The reactivity of p–^{11}B and p–^{7}Li fuels is less than that of the DT fuel, or the ignition of the advanced fuels becomes difficult in comparison with the DT fuel, this consequence is predicted above. Therefore, the densities of the p–^{11}B and p–^{7}Li reactions should be increased to 120 and 180 times that of the solid state, respectively. These numerical results open the ignition possibilities of non-radioactive reactions by the shock strong of laser driven plasma block ignition.

6. Conclusions

A series of computational techniques are used to investigate spherical solid fuels for the shock ignition of a laser driven plasma block. The numerical results are obtained from the electron and ion temperature equation. With the studied conditions, it is found that the accelerated plasma block can provide shock waves in fuel and it is favorable to the increase of density according to the Rankyne–Hugonit simplified analytical model. Firstly, the compression yield is dependent on the laser with a longer duration pulse for the initial compression. Secondly, the plasma density needs to be highly compressed, which is done by the generated shock wave in fuel. It is also due to the velocity condition and the ρR parameter; the spherical DT fuel density should be increased to 75 times that of the solid state. New conditions of the advanced fuel ignition for the plasma block ignition scheme by using the density dependence of hydrodynamic equation in depth are obtained to be $E_{\mathrm{tp}-^{11}\mathrm{B}}{}^{*}=6\times10^{12}$ J/m^2 and $E_{\mathrm{tp}-^{7}\mathrm{Li}}{}^{*}=6.3\times10^{12}$ J/m^2 with $T^{*}_{\mathrm{p}-^{11}\mathrm{B}}=87$ keV and $T^{*}_{\mathrm{p}-^{7}\mathrm{Li}}=69$ keV, respectively. These values are the ignition thresholds. By comparing the threshold values for the p–^{11}B and p–^{7}Li fuels for $r\neq0$ and $x=0$ layers, we can conclude that due to increasing the self heating of alpha particles and the higher alpha particle energy in comparison with that for the p–^{11}B reaction, $E_{\mathrm{tp}-^{7}\mathrm{Li}}{}^{*}$ is further reduced. The delay of ion heating is important for the ignition of non-radioactive solid fuels at $r\neq0$ layers, and the time is shifted from 10^{-8} s to 10^{-7} s. Finally, to achieve clean energy through the non-radioactive reactions by a strong shock of laser driven plasma block ignition, we need densities 120 and 180 times of the solid state for p–^{11}B and p–^{7}Li reactions, respectively. Non-radioactive fusion will be achieved with these new conditions.

Acknowledgment

The authors would like to thank Dr. Mohammad Jahangiri at the I. A. University for discussion, and especially thank Sevda Salehi and Arash Malekynia for their useful help.

References

[1] Atzeni S 1995 *Jpn. J. Appl. Phys.* **34** 1986
[2] Scheffel C, Stening R J, Hora H, HÖpfl R, Martinez-Val J M, Eliezer S, Kasotakis G, Piera M and Sarris E 1997 *Laser and Particle Beams* **15** 565
[3] Yamanaka Ch 2002 *Laser and Particle Beams* **20** 5
[4] Hora H, Miley G H, Flippo K, Lalousis P, Castillo R, Yang X, Malekynia B and Ghoranneviss M 2011 *Laser and Particle Beams* **29** 353
[5] Malekynia B and Razavipour S S 2012 *Chin. Phys. B* **21** 125201
[6] Betti R, Zhou C D, Anderson K S, Perkins L J, Theobald W and Solodov A A 2007 *Phys. Rev. Lett.* **98** 155001
[7] Nuckolls J H and Wood L 2002 *CA: Lawrence Livermore National Laboratory Preprint* UCRL-JC-149860
[8] Badziak J 2007 *Opto-electronics Review* **15** 1
[9] Ban H Y, Gu Y J, Kong Q, Li Y Y, Zhu Z and Kawata S 2011 *Chin. Phys. Lett.* **29** 035202
[10] Hora H, Miley G H, Ghoranneviss M, Malekynia B, AziziN and He X T 2010 *Energy Environmental Science* **3** 479

[11] Ghoranneviss M, Salar Elahi A, Hora H, Miley G H, Malekynia B and Abdollahi Z 2012 *Laser and Particle Beams* **30** 459
[12] Ghoranneviss M, Salar Elahi A, Hora H and Sari A H 2012 *J. Fusion Energy*
[13] Chu M S 1972 *Physics of Fluids* **15** 413
[14] Lalousis P and Hora H 1983 *Laser and Particle Beams* **1** 283
[15] Ray P S and Hora H 1976 *Nuclear Fusion* **16** 535
[16] Hora H and Ray P S 1978 *Zeitschrift F. Naturforschung* A33 890
[17] Bethe H A 1934 *Handbuch der physik* **24 1** 497
[18] Hora H 1981 *Nuovo Cimento* **64B** 1
[19] Malekynia B, Ghoranneviss M, Hora H and Miley G H 2009 *J. Fusion Energ.* **28** 135
[20] Kammash T 1975 *Fusion Reactor Physics: Principles and Technology* (Ann Arbor: Ann Arbor Science)
[21] Niu K 1989 *Nuclear Fusion* (Cambridge: Cambridge University Press)
[22] Hora H, Miley G H, Azizi N, Malekynia B, Ghoranneviss M and He X T 2009 *Laser and Particle Beams* **27** 491
[23] Fraley G S, Linnebur F J, Mason R J and Morse R L 1974 *Phys. Fluids* **17** 474