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Energy deposition of heavy-ion beams in neutronless fusion reaction

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Abstract. Recent advances in laser-plasma accelerators have made possible the production of high-power beams with very low divergence. In this paper, the carbon heavy-ion beam was used to provide optimal conditions for the ignition of P–^{11}B clean fuel pellets using the Deira-4 simulation code. The calculations showed that generating maximum ion heating of about 140 keV requires a laser with an intensity of 10^{21} W/cm^2 and a radiation time of 20 ps, which provide medium heating conditions for ignition.

Keywords. Heavy-ion beam; laser-plasma accelerator; Deira-4 simulation code; stopping power.

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1. Introduction

Compared to other methods for generating energy, the nuclear fusion method has been more widely considered because fuel sources are easily available, there is no radiation emission, no contamination of the environment, and energy can be mass produced. Fast ignition-inertial confinement fusion (FI-ICF) method is an example for fusion methods [1]. The fast ignition method was initially discussed in the 1960s, by Harrison [2] and Maisonnier [3]. Its main idea was presented by Tabak *et al* in 1994. To achieve a higher gain using this method, the compression and ignition phases must be separated from each other. First, the fuel capsule was pre-compressed by a long-pulse (ns) (laser beams, X-rays) as the driver, and then the compressed fuel was burnt by a secondary pulse whose intensity is greater than that of the initial pulse (an appropriate trigger for fast ignition). An intense short-pulse (ps) ultra-intense (about $\sim 10^{20}$ W cm^{-2}) particle beam of fast electrons, protons, or other ions could be used as the ignitor. Based on the initial idea of fast ignition, high-intensity lasers were used to increase the dense fuel temperature [4]. Recently, ion beam has been proposed as a more suitable option for hot spot ignition. Hence, we do not need the laser to interact with fuel plasma anymore. The ion beam is used because short-range electrons can be produced, energy leakage is less and divergence of the ion beam in the fuel is less [5]. Besides, a new scientific opportunity has recently been provided for using the target normal sheath acceleration (TNSA) by replacing petawatt lasers with the proton beam. Essentially, the idea is to use a laser with an intensity of 10^{20} W/cm^2 to radiate onto a foil outside the fuel capsule, create an electron population and finally produce high-energy ions [6].

The production of energetic ions of order MeV has been observed in various experiments using radiated lasers with high intensities on different fuel targets such as solid foil [7–11]. Roth *et al* [12] have shown that the production of a proton beam with energy equal to 15–23 MeV by the TNSA accelerator method could ignite the pre-compressed hot spots. In this case, the threshold energy was estimated to be about 10–100 kJ [13,14]. Practical access to such an idea comes with many problems due to the low gain of the laser–foil interaction (10%), low flux of the accelerated ions and the properties of the particle-energy Maxwell distribution. In the year 2002, Esirkepov *et al* [15] obtained protons with an energy of 60 MeV using a dual-purpose target composed of heavy and light atoms. It was found that the TNSA could not accelerate ions to higher energies and produce ion beams with low divergence. It is essential to use accelerators that can accelerate ions to high energies at low cost and with affordable energy.

The idea of using the radiation pressure acceleration method (RPA accelerator) is considered as an optimal idea in this design. In 2002, Esirkopov *et al* [15]

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achieved an energy of 1.5 GeV by a PIC simulator using a circular polarisation laser beam.

These two accelerators are based on the acceleration of the ions from a very thin foil in the presence of electrostatic fields due to the interaction of laser pulses with plasma whose laser intensity is more than 10^{18} W/cm^2. A very thin foil can be irradiated by a high-intensity laser beam. Energetic and focussed ions are obtained by laser radiation from the surface of an ionised dielectric foil. If the target is very thin, all ions will accelerate before the end of the desired pulse, which is followed by complete cavitation. This method is referred to as the light sail (LS) method. The method is regarded highly due to its high efficiency, especially within the relativistic limit, and the availability of high energy within a relativistic limit including high-frequency lasers [16–21]. Based on experiments and numerical simulations, this method can be used to get quasi-monoenergetic proton beams with energies more than 100 MeV [22]. Using ions heavier than protons leads to a decrease in the energy threshold [23]. In 2013, Domanski *et al* [24] achieved 1 GeV energy for proton and 10 GeV energy for carbon by simulating a circular polarisation laser beam. By reducing the thickness and increasing the intensity of the incident laser beam, it is possible to achieve a proton beam of 7.7 GeV energy and a carbon beam of 72 GeV energy [24]. To achieve the ignition conditions, the use of ions heavier than proton has been proposed due to the better transport, higher stopping power and complete energy infusion in a given volume [25]. The heavier particles require energy more than that of the protons to be able to penetrate deeper into the plasma. This implies that each heavier particle deposits its higher amount of energy in the environment. Therefore, the total number of particles needed for ignition is very small [26]. This phenomenon reduces various design problems of the target [27]. In 2014, Fernández *et al* [11] proposed the use of heavier ions, such as carbon, lithium and beryllium. The heavier ions transfer more energy due to more mass. Also, they can infuse their energy more than lighter ions such as protons. Due to the limitation of the number of beams produced, it seems that the heavier ion beams are more suitable for ignition because their energy infusion is better within the relativistic energy limit [28].

The remainder of this paper is organised as follows. Section 2 introduces the proposed fuel. Section 3 presents the stopping power model of the fast ion in the proposed plasma medium. Section 4 discusses the Deira-4 simulation code and the energy-deposit conditions for the heavy carbon ion beam, the optimum laser power and the carbon beam energy for the proposed fusion process which is calculated using the Deira-4 simulation code. Section 5 gives an analysis of the results of the simulation. Finally, §6 presents the concluding remarks.

2. Advanced fuel

Deuterium–tritium fuel is the main controlled fusion fuel at the temperatures available in fusion reactors due to the largest cross-section. However, the production of radioactive and energetic neutrons leads to a waste of energy, destruction of the reactor structure, and biological and environmental hazards. For this reason, many studies have been conducted to investigate how to replace the current fuel with neutronless fuel [29]. The P–^{11}B reaction is a reliable fuel source for fusion reactors due to the absence of radioactive neutrons.

$$p + {}^{11}\mathrm{B} \rightarrow 3\alpha + (8.68)\ \mathrm{MeV}$$

Of course, a nuclear fusion process with such fuels requires an average ion and electron temperature of more than 100 keV in dense plasma [30].

3. Stopping power model

The stopping power of hot plasma plays a key role in the inertial confinement fusion because it provides conditions for the thermonuclear ignition and burning. For this purpose, the energy deposition of ions in the plasma due to ionisation and excitation processes of Coulomb forces should be facilitated by appropriate mathematical equations. In this regard, various stopping power models have been proposed for calculating the energy deposition of ions. The model for the high-energy beam in the relativistic range is different from the current model of the stopping power due to the different physical process and the absence of relativistic corrections. The current model is mainly used for the transport of low-energy charged particles of fusion products in fusion plasma. The proposed theoretical model for the stopping power of fast-relativity ions was presented by Basko in 1984, which is also used in the Deira-4 next-dimensional simulation code. In this study, the simulations were performed using the three-temperature one-dimensional hydrodynamic Deira-4 code that is written by Mikhail Basko in Fortran 77 [31]. Deira-4 code is a physical-mathematical model for generating a numeric code that is used to simulate inertial fusion targets by the ion beam driver. The Deira-4 code is a three-temperature code obtained by the finite-difference method (FDM). This code can design fusion targets in three geometries, namely flat, cylindrical and spherical [32].

In this model, the Coulomb energy loss is calculated for fast ions with an energy range of 0.1 MeV/amu $\leq$

$E_1 \leq 1\,\mathrm{GeV/amu}$, the temperature of $0 < T < 300\,\mathrm{keV}$ and a density of $0 < \rho < 10^6\,\mathrm{g/cm^3}$. According to Basko's theory, stopping power can be expressed as follows:

$$-\frac{1}{\rho}\frac{\mathrm{d}E_1}{\mathrm{d}x} \equiv S = S_{\mathrm{be}} + S_{\mathrm{fe}} + S_{\mathrm{fi}} + S_{\mathrm{nu}}, \tag{1}$$

where S_{be}, S_{fe}, S_{fi} and S_{nu} determine the stopping power of the bound and free electrons, the plasma free ions and the bare nuclei, respectively. The stopping power of the fast ions by the bound electrons is expressed by Basko as follows [32]:

$$S_{\mathrm{be}} = \frac{4\pi e^4 Z_{1\mathrm{ef}}^2}{m_{\mathrm{e}}\upsilon_1^2}\left(\frac{Z_2 - y}{A_2 m_{\mathrm{A}}}\right) \times \left[L_{\mathrm{be}} - \mathrm{Ln}\left(1 - \frac{\upsilon_1^2}{c^2}\right) - \frac{\upsilon_1^2}{c^2}\right], \tag{2}$$

where $eZ_{1\mathrm{ef}}$ is the average charge of the fast ions that are moving with velocity υ_1, $(Z_2 - y)$ is the number of electrons bounded by the atom, m_{A} is the atomic mass and L_{be} is the Coulomb logarithm. The Coulomb logarithm within the limit $L_{\mathrm{be}} \gg 1$ is described by

$$L_{\mathrm{be}} = \ln\left(\frac{P_{\max}}{P_{\min}}\right) \tag{3}$$

and

$$P_{\max} = 2m_{\mathrm{e}}\upsilon_1 \tag{4}$$

$$P_{\min} = \left[\left(\gamma Z_{1\mathrm{ef}} e^2\bar{\omega}/\upsilon_1^2\right)^2 + (\hbar\bar{\omega}/\upsilon_1)^2\right]^{1/2}, \tag{5}$$

where $\bar{\omega}$ is the average of the atomic electron excitation frequency and the Eulerian constant $\gamma = 0.577$.

The approximate value is obtained according to (6):

$$\hbar\bar{\omega} = g(y)\varepsilon_{n,l,j}(y), \tag{6}$$

where $\varepsilon_{n,l,j} = \varepsilon_{n,l,j}(y)$ is the separation energy of an electron in the sublayer n, l, j. Using $g_0 = g(y_0)$ and $g(Z_2 - 1) = g_{\mathrm{H}} = 1.105$, we have the following equations:

$$g(y) = \begin{cases} g_0 & 0 < y \leq y_{\mathrm{c}} \\ g_0 + (g_{\mathrm{H}} - g_0)(y - y_{\mathrm{c}})(Z_2 - 1 - y_{\mathrm{c}}) & y_{\mathrm{c}} < y < Z_1 - 1 \\ g_{\mathrm{H}} & Z_2 - 1 \leq y < Z_2 \end{cases} \tag{7}$$

The stopping power of the fast ions by the free electrons of plasma is expressed by the following equation:

$$S_{\mathrm{fe}} = \frac{4\pi e^4 Z_{1\mathrm{ef}}^2}{m_{\mathrm{e}}\upsilon_1^2}\frac{yG(x_{\mathrm{e}})}{A_2 m_{\mathrm{A}}}\left[L_{\mathrm{ef}} - \ln\left(1 - \frac{\upsilon_1^2}{c^2}\right) - \frac{\upsilon_1^2}{c^2}\right]. \tag{8}$$

The function $G(x_{\mathrm{e}})$ is defined as follows:

$$G(x_{\mathrm{e}}) = \frac{2}{\sqrt{\pi}}\left[\int_0^{x_{\mathrm{e}}} \exp\left(-t^2\right)\mathrm{d}t - x_{\mathrm{e}}\exp\left(-x_{\mathrm{e}}^2\right)\right] \approx \left(1 + 1.33x_{\mathrm{e}}^3\right)^{-1}. \tag{9}$$

Also, we have

$$x_{\mathrm{e}} = \left(\frac{m_{\mathrm{e}}\,\upsilon_1^2}{2kT_{\mathrm{ef}}}\right)^{1/2}, \quad x_{\mathrm{i}} = \left(\frac{m_{\mathrm{A}}A_2\,\upsilon_1^2}{2kT_{\mathrm{i}}}\right)^{1/2} \tag{10}$$

$$kT_{\mathrm{ef}} = \left[(kT_{\mathrm{e}})^2 + \left(2^{1/3}\pi\,\hbar^2 n_{\mathrm{e}}^{2/3}/m_{\mathrm{e}}\right)^2\right]^{1/2} \tag{11}$$

$$L_{\mathrm{fe}} = \ln\left[1 + \Lambda_{\mathrm{fe}}/\left(1 + 0.5/\Lambda_{\mathrm{fe}}^{1/2}\right)\right] \tag{12}$$

$$m_{\mathrm{e}}\upsilon_{\mathrm{ef,e}}^2 = 2kT_{\mathrm{ef}}\,\eta\,(x_{\mathrm{e}}), \quad m_{\mathrm{A}}A_2\upsilon_{\mathrm{ef,i}}^2 = 2kT_{\mathrm{i}}\,\eta\,(x_{\mathrm{i}}). \tag{13}$$

The quantity $n_{\mathrm{e}} = \rho y/A_2 m_{\mathrm{A}}$ is the volume density of free electrons.

The stopping power of the fast ions with the plasma ions plays an important role at the end of the penetration depth in hot plasma with $xe \ll 1$ or cool plasma $E_1 \leq 0.5\,\mathrm{MeV/amu}$ with $Z_1 \gg 1$ and $Z_2 \gg 1$. The ion collision can be divided into distant collision and close collision. Here, the effective parameter of the collision, $r = r_s$ is considered to be the boundary between these two types of collisions. Also, the corresponding contribution of their participation is denoted by S_{fi} and S_{nu} in the total stopping power.

When $r \gg r_s$, the beam and target ions behave like point charges $Z_{1\mathrm{eF}}$ and ey in dealing with each other, and when $r \ll r_s$, the nuclei of colliding ions penetrate into the cloud of electrons and are repatriated as point charges eZ_1 and eZ_2. In this model, the $\Lambda_{\mathrm{fi}} = P_{\max}/P_{\min}$ parameter can be obtained by the following relation using the Debye screening theory for free-electron collisions:

$$\Lambda_{\mathrm{fi}} = \min\left\{\frac{2M_0\upsilon_{\mathrm{ef,i}}^2\, r_{\mathrm{ef}}^*}{\left(\hbar^2\,\upsilon_{\mathrm{ef,i}}^2 + \gamma^2\, Z_{1\mathrm{ef}}^2 y^2 e^4\right)^{1/2}};\ \frac{r_{\mathrm{ef}}^*}{r_s}\right\}, \tag{14}$$

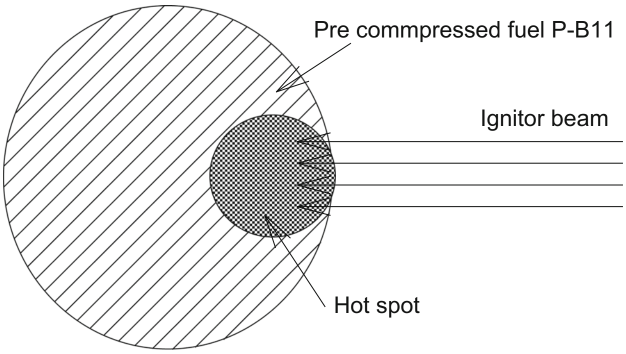

Figure 1. A scheme of the energy-beam deposition ignition and the formation of hot spots.

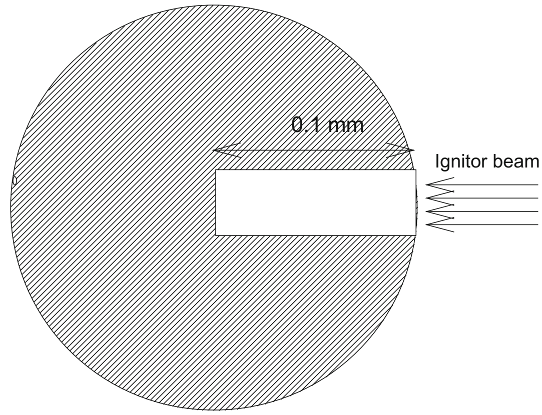

Figure 2. A view of the pellet.

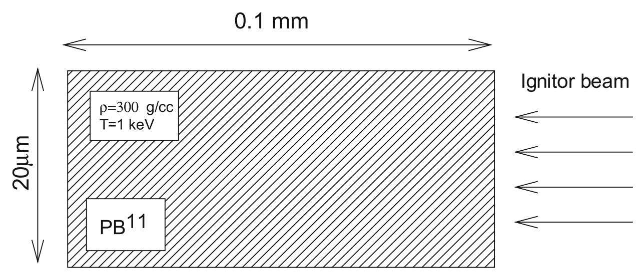

Figure 3. A 2D image of a fuel pellet under ion beam radiation.

where $M_0 = m_A A_1 A_2/(A_1 + A_2)$ is the reduced mass of the collider ions and $\upsilon_{\mathrm{ef,i}}$ is the effective speed of the test ion. Assuming that the range is equal to the heavy metal ion (HMI) shift along its initial line, the stopping power of the plasma-free ions, S_{fi}, is obtained as follows:

$$S_{\mathrm{fi}} = \frac{4\pi e^4 Z_{\mathrm{1ef}} y^2}{m_A A_2 \upsilon_1^2} \frac{(1 + A_2/A_1)^{1/2}}{m_A A_2} G(x_i) L_{\mathrm{fi}}. \qquad (15)$$

Heavy ions gradually approach an almost direct path except for the end of the path, which is important for nuclear collisions. The penetration depth along the heavy ion can be obtained by the following equation:

$$R = \int_0^E \frac{\mathrm{d}E}{\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_e + \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_i}. \qquad (16)$$

In eq. (16), $(\frac{\mathrm{d}E}{\mathrm{d}x})_e$ and $(\frac{\mathrm{d}E}{\mathrm{d}x})_i$ are the contribution of the electron and ion energy, respectively.

4. Simulation model

We consider the equimolar P–^{11}B fusion fuel, which is pre-compressed in the fast fusion mode and then exposed to carbon-ion beam radiation. At the ignition stage, the ion beam generates a hot spot and the burn wave is transferred to the surrounding cool volume (figure 1).

The ignition stage is examined by the one-dimensional Deira-4 code. The optimal mode of ignition is the case in which the ignition occurs with the lowest input energy. The equimolar P–^{11}B fusion fuel is considered with 300 g/cm^3 density and a temperature of 1 keV in the ignition stage. To better explain the changes in the fuel parameters, the area of the spherical fuel pellet is considered as flat, according to figure 2.

A two-dimensional image of the flat geometry is considered with a length of 0.1 mm and a width of 20 micrometres as shown in figure 2. The geometry of the flat is divided into 60 cells so that the 60th cell is the first cell to be exposed to ion beam radiation, and the heating of the fuel cell is conducted from both cells (figure 3).

To start the ignition process, the ignitor beam pulse should be radiated onto the fuel at a time shorter than that of the standstill time. Otherwise, after this time, the fuel will not have the required density to initiate the ignition with the expansion of the fuel. In this case, there is no possibility of ignition. To extract the optimal energy for carbon ion, the carbon ion beam with 100, 200, 300 and 400 MeV energy is radiated onto a pre-compressed target at 1 keV with 300 g/cm^3 density. Then, by describing the results extracted from the simulation performed by the Deira-4 code, the optimal energy required for the proposed fuel pellet is determined.

5. Simulation results

The ionic temperature of fuel pellets changes as a function of the penetration depth. Figure 4 shows the related trend for a carbon beam driver. The driver has different energies of 100, 200, 300 and 400 MeV depending on the physical conditions of the fuel pellets, i.e., tempearature = 1 keV, density = 300 g/cm^3 and laser intensity = 10^{20} W/cm^2. Since the ignition temperature of P–^{11}B

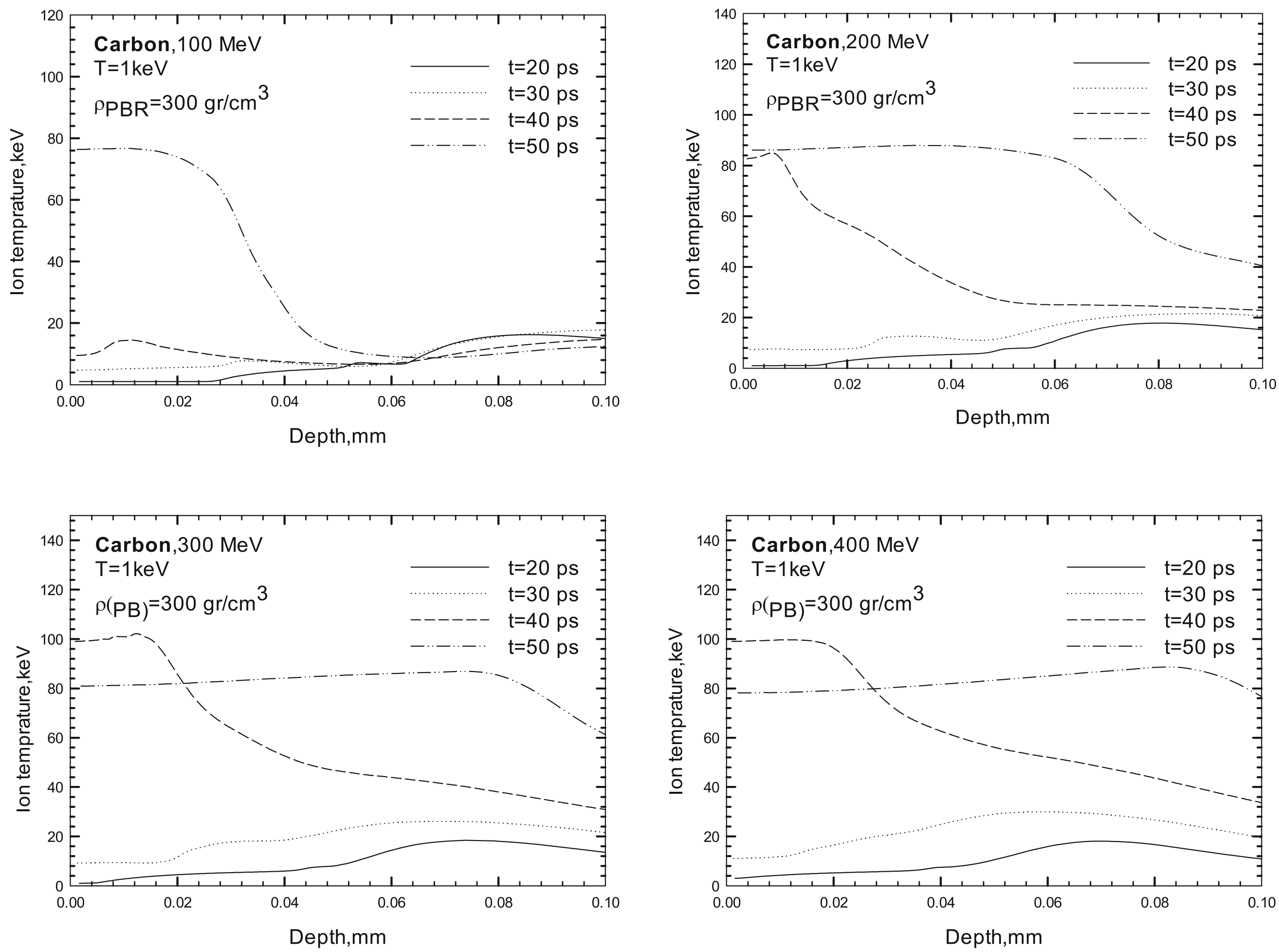

Figure 4. The variation of ion temperature based on the penetration depth when laser intensity $= 10^{20}$ W/cm^2 laser intensity for different energies.

fuel pellets is higher than 100 keV, the required minimum temperature of the fuel will not be achieved by increasing time for laser intensities $10^{20}\ \mathrm{W/cm^2} \leq I_L$ when temperature $=$ 1 keV and density $= 300\ \mathrm{g/cm^3}$. Therefore, the ignition temperature condition cannot be achieved even with an increase in the carbon beam energy due to waste processes. Hence the burning of fuel pellets will not happen.

Similarly, to provide minimum fuel ignition conditions, the calculations for a laser with 10^{21} W/cm^2 intensity are renewed in the same physical condition. According to the results presented in figure 5, the minimum ion temperature required for the combustion of the fuel pellet is provided for a period of 20 ps at a depth of 0.55 mm. It can be seen that the possibility of burning decreases with increase in the radiation time. This is due to the expansion of the fuel and cooling of the plasma.

The depth of penetration in matter depends on the absorbed energy changes due to the interaction of ions with matter during stopping, dispersing and non-elastic interactions. The slow-down and energy loss of ions in matter lead to the ionisation and formation of the Bragg peak at the end of the path. The variation of the mass range of carbon beam in terms of the plasma temperature is calculated based on the stopping power for the minimum energy of the input carbon beam in the physical conditions. This has been achieved with a background temperature of 1 keV and a density of 300 g / cm^3, as shown in figure 6. For example, the location of the hot spot can be calculated to be 0.5 mm by a carbon ion beam whose energy is equal to 300 MeV for P–^{11}B fuel pellets by converting the mass range to the longitudinal board.

In the following, the time-dependence of the temperature of ions and electrons of the fuel pellets is calculated by Deira-4 simulation code for the carbon heavy-ion beam. The beam whose energy is equal to 300 MeV has a laser intensity of 10^{21} W/cm^2 and a radiation time of 20 ps. It is shown in figure 7 in its physical condition.

The calculations showed that due to the ion energy deposition, the electron temperature is lower than the ion temperature in fuel pellets so that the maximum ion

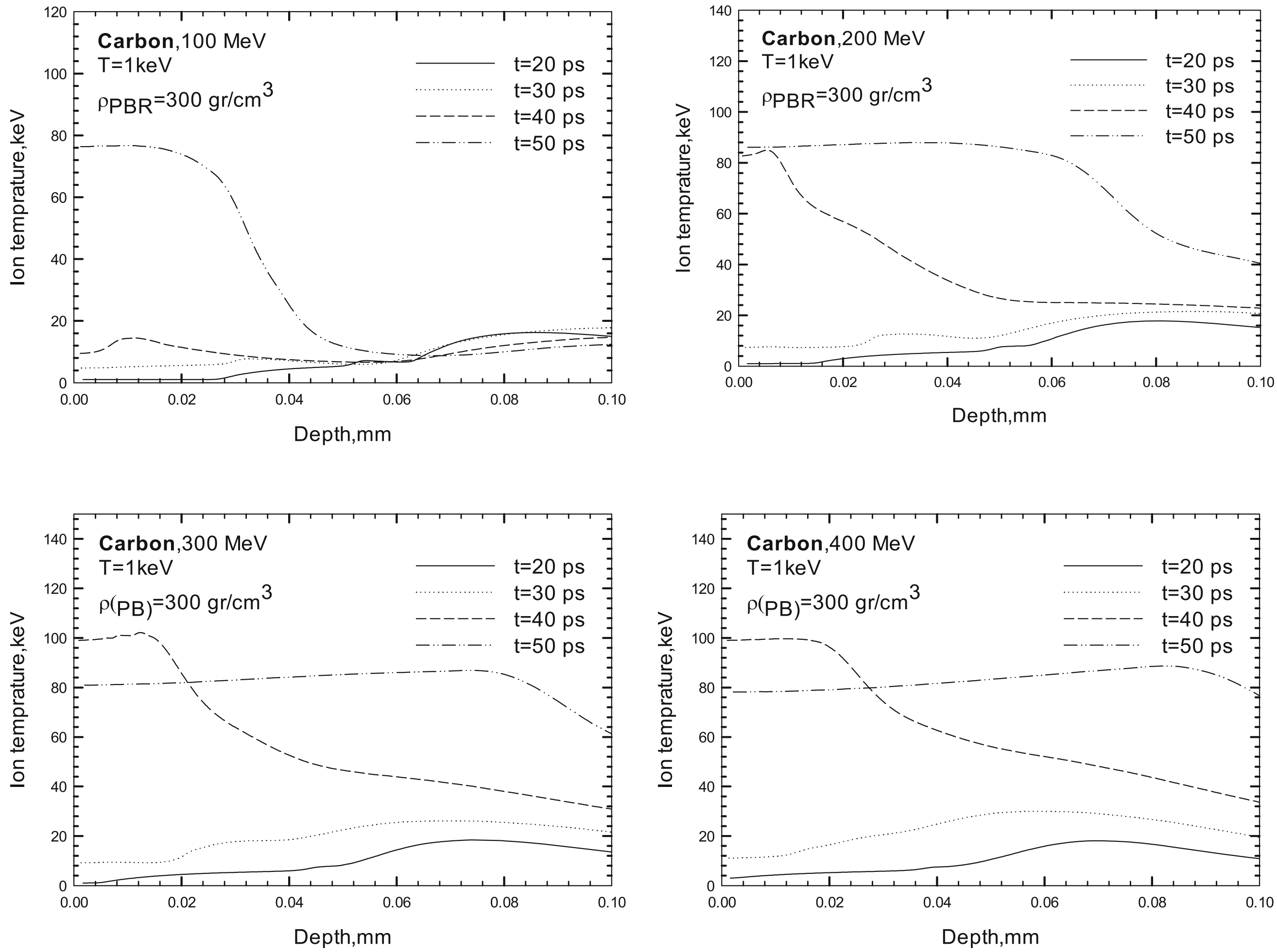

Figure 5. The variation of ion temperature based on the penetration depth when laser intensity $= 10^{21}\ \mathrm{W/cm^2}$ for different energies.

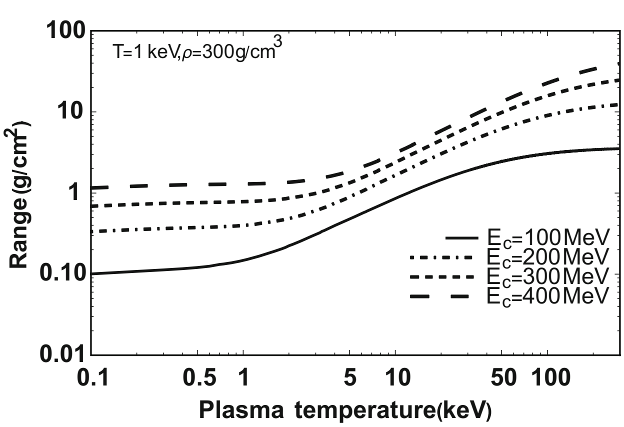

Figure 6. The mass range of carbon ion beam in P–^{11}B fuel vs. plasma temperature with a background temperature of 1 keV and density of 300 g/cm^3 for different energies.

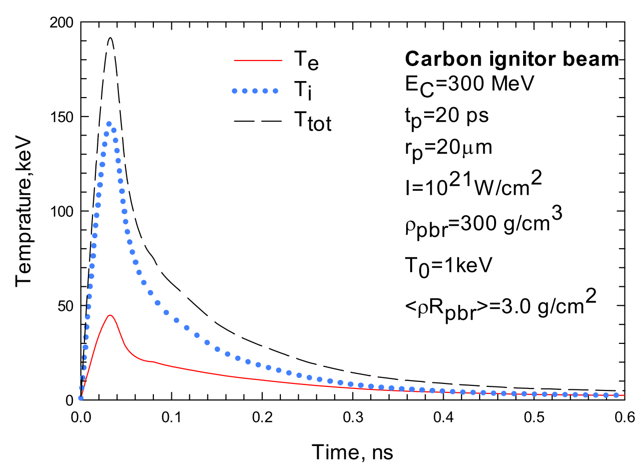

Figure 7. The time-dependence of ion and electron temperature with a carbon ion beam ignitor.

heating of above 140 keV occurs during the compression time of 40 ps. Besides, the electron and ion temperature will decrease when the time is increased until the system achieves thermal equilibrium.

6. Conclusion

The optimum ignition conditions of the P–^{11}B advanced fusion fuel were simulated by an ignitor heavy-carbon ion beam. For this purpose, the P–^{11}B fuel ignition conditions for a laser with 10^{20} and 10^{21} W/cm^2 intensities and a radiation time of 20 ps were simulated in physical conditions. In doing so, a background temperature of 1 keV and density of 300 g/cm^3 for different energies of the carbon beam, and the Deira-4 simulation code were considered. The simulation results showed that the minimum ion temperature conditions ($T > 100$ keV) of the P–^{11}B fuel pellet are provided by a laser beam whose energy = 300 MeV and intensity = 10^{21} W/cm^2.

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