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Citation: Chin. Phys. B, 2024, 33 (**11**): 115202. DOI: 10.1088/1674-1056/ad71b8
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A model for fast electron-driven high-density plasma in the double-cone ignition scheme

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(Received 13 May 2024; revised manuscript received 19 August 2024; accepted manuscript online 21 August 2024)

A model for fast electron-driven high-density plasma is proposed to describe the effect of injected fast electrons on the temperature and inner pressure of the plasma in the fast heating process of the double-cone ignition (DCI) scheme. Due to the collision of the two low-density plasmas, the density and volume of the high-density plasma vary. Therefore, the ignition temperature and energy requirement of the high-density plasma vary at different moments, and the required energy for hot electrons to heat the plasma also changes. In practical experiments, the energy input of hot electrons needs to be considered. To reduce the energy input of hot electrons, the optimal moment and the shortest time for injecting hot electrons with minimum energy are analyzed. In this paper, it is proposed to inject hot electrons for a short time to heat the high-density plasma to a relatively high temperature. Then, the alpha particles with the high heating rate and $P\mathrm{d}V$ work heat the plasma to the ignition temperature, further reducing the energy required to inject hot electrons. The study of the injection time of fast electrons can reduce the energy requirement of fast electrons for the high-density plasma and increase the probability of successful ignition of the high-density plasma.

Keywords: fast electrons, the high-density plasma, alpha particles, double-cone ignition scheme, the optimal moment, the shortest time

PACS: 52.50.Gj, 52.55.Pi, 52.58.–c **DOI:** 10.1088/1674-1056/ad71b8

1. Introduction

In the study of inertial confinement fusion (ICF),[1–5] the current ignition schemes include the central ignition[6–8] and fast ignition schemes.[9–11] Due to equipment limitations, the central ignition and the fast ignition are difficult to achieve for ignition and energy gain. To tackle this difficulty, Zhang *et al.*[12] proposed a new ignition scheme: the double-cone ignition (DCI) scheme. This scheme can effectively decrease the energy requirements of the compression and heating laser pulses, improving the stability of the compression and ignition processes. The DCI scheme consists of four individually controllable processes: quasi-isentropic compression, acceleration, head-on collision, and fast heating. In the head-on collision process, two low-density plasmas collide to form a high-density plasma with a duration of about 100 ps. The high-density plasma has a temperature up to 100 eV and an areal density of greater than 0.8 $\mathrm{g/cm^2}$. Subsequently, fast electrons are injected into the high-density plasma to make it reach the ignition temperature and complete the implosion. Therefore, the effect of fast electrons on the temperature of the high-density plasma is critical to the success of the ignition.

There are few studies on the effect of fast electrons on the temperature and pressure of the high-density plasma in the DCI scheme. Consequently, a model is proposed for the variation of the temperature and inner pressure of the high-density plasma when fast electrons are injected. Since the two low-density plasmas still have some velocity after collision, the density[13] and volume of the high-density plasma formed by the collision will change. According to the Lawson criterion, the ignition temperature of the high-density plasma changes when the density and volume of the plasma change. During the existence of the high-density plasma status, the energy required for the high-density plasma to reach the ignition temperature varies at different moments, and the time for fast electrons to heat the plasma also varies. When the injected fast electrons can directly heat the high-density plasma to the ignition temperature, the optimal moment of injecting fast electrons is worth studying when fast electrons with the same energy heat the plasma to ignition temperature takes the shortest time. When the time for injecting fast electrons is limited, or the efficiency for the energy deposition of fast electrons is low, and fast electrons may not be able to heat the plasma directly to the ignition temperature. For this case, we consider injecting fast electrons for a short time to heat the plasma to a relatively high temperature. As the temperature of the plasma increases, the number of alpha particles produced rises, and the heating rate of alpha particles increases. The plasma can also be heated to ignition temperature by alpha particles and $P\mathrm{d}V$ work when fast electrons are not injected. Therefore, it is worthwhile to study when the injection of fast electrons takes

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the shortest time and the minimal energy. The study of the injection time of fast electrons can reduce the plasma requirement for the efficiency of energy deposition of fast electrons. It can also provide a reference value for the practical injection of fast electrons.

In Section 2, we propose a model and a numerical method for the fast heating process of the DCI scheme. In Section 3, the optimal moment and the shortest time for injecting fast electrons to heat the plasma to reach the ignition temperature are analyzed, and the effect of variations in the temperature and density of fast electrons on the injection time is analyzed. Some conclusions of this work are given in Section 4.

2. A model and numerical method for the fast heating process

This section is devoted to a brief description of the model and the numerical method for the fast heating process of the DCI scheme. Subsection 2.1 describes the model for fast electron-driven high-density plasma in the fast heating process of the DCI scheme. The process of volume change in the high-density plasma due to collisions is discussed in Subsection 2.2. A numerical method for solving the temperature and inner pressure equations of the high-density plasmas is introduced in Subsection 2.3.

2.1. The model for fast electron-driven high-density plasma

During the head-on collision process of the DCI scheme, two compressed plasmas with the same initial density collide. After the collision, the high-density plasma status is formed and sustains approximately 100 ps, which doubles in density. The high-density plasma status has a temperature up to 100 eV and an areal density of greater than 0.8 g/cm^2.[12] Although the density of the high-density plasma has reached the threshold for ignition, its temperature is still far from the ignition temperature. During the existence of the high-density plasma status, fast electrons are injected into the high-density plasma so that the high-density plasma reaches the ignition temperature. Since there are few models of high-density plasmas in the fast heating process, a model is proposed for the variation of the temperature and pressure of the high-density plasma when fast electrons are injected.

The high-density plasma status is nearly an ellipsoid.[12] Fast electrons are injected into the ellipsoidal high-density plasma, as shown in Fig. 1(a). This study focuses on the physical mechanisms and general trends of the variations in the temperature and density of the high-density plasma during the fast heating process. Therefore, the model of injecting fast electrons into the high-density plasma during the fast heating process is simplified. To simplify the physical model, we assume that ellipsoidal high-density plasma is circular in the YOZ plane. The lengths of the two semiaxes $(r_\mathrm{p}, r_\mathrm{p})$ of the ellipsoidal high-density plasma remain constant in the YOZ plane, and the semiaxial length (r_b) on the OX axis changes, when two low-density plasma collide. A model for fast electrons injected into the OY axis of the circular high-density plasma is shown in Fig. 1(b). The density and temperature of the circular high-density plasma are uniformly varying when fast electrons are injected. Notably, this model is only applicable to the DCI scheme.

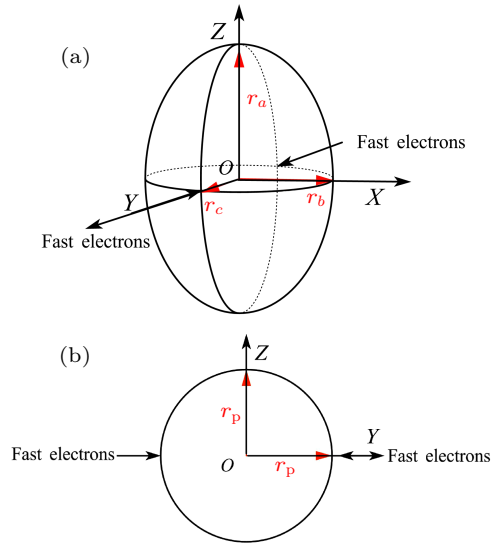


Fig. 1. (a) Fast electrons are injected into the OY axis of the ellipsoidal high-density plasma. The lengths of the three semiaxes of the ellipsoidal high-density plasma are r_a, r_b, and r_c, respectively. (b) The model for injecting fast electrons into the OY axis of the circular high-density plasma is shown. The radius of the circular high-density plasma is r_p.

The influence of other physical factors on the plasma needs to be considered besides fast electrons when fast electrons are injected into the high-density plasma. Since there are few models of the DCI scheme, the one-dimensional model for fast electron-driven high-density plasma is established by making some improvements to Springer *et al.*'s model.[14] Springer *et al.* consider the effect of various physical factors on the hot spot, including alpha heating, radiation loss, conduction losses, and $P\mathrm{d}V$ work in the central ignition. The equations of hot-spot inner pressure (P_hs) and temperature (T_hs) are expressed as

$$\frac{\mathrm{d}P_\mathrm{hs}}{\mathrm{d}t} = \frac{2}{3V}\left(Q_\alpha - Q_\mathrm{rad} - \frac{5}{2}P_\mathrm{hs}\frac{\mathrm{d}V}{\mathrm{d}t}\right), \tag{1}$$

$$\frac{\mathrm{d}T_\mathrm{hs}}{\mathrm{d}t} = \frac{2T_\mathrm{hs}}{3P_\mathrm{hs}V}\left(f_\alpha Q_\alpha - Q_\mathrm{rad} - Q_\mathrm{cond} - P_\mathrm{hs}\frac{\mathrm{d}V}{\mathrm{d}t}\right), \tag{2}$$

where Q_α, Q_rad, and Q_cond are the rate equations for alpha heating,[15] radiative leakage,[16] and conduction losses,[14]

$$\begin{aligned} Q_\alpha = {} & 5.6\times10^{-3}\left(\frac{P_\mathrm{hs}}{202.8}\right)^2\left(\frac{r_\mathrm{hs}}{0.004}\right)^3 \\ & \times\exp\left[38.091 - 2.2523\exp\left(\frac{1-T_\mathrm{hs}}{0.68238}\right)\right. \\ & \left. -4.265\exp\left(\frac{1-T_\mathrm{hs}}{4.1743}\right)\right]W, \end{aligned} \tag{3}$$

$$Q_{\rm rad} = 4.24\times10^{14}\left(\frac{P_{\rm hs}}{202.8}\right)^2\left(\frac{r_{\rm hs}}{0.004}\right)^3 {T_{\rm hs}}^{-1.3023} W, \quad (4)$$

$$Q_{\rm cond} = \frac{8\pi}{3}\frac{1}{1+\beta}KT_0x_0y_0z_0\left(\frac{1}{{x_0}^2}+\frac{1}{{y_0}^2}+\frac{1}{{z_0}^2}\right)W, \quad (5)$$

where $r_{\rm hs}$ is the radius of the hot spot, V the hot-spot volume, and $P_{\rm hs}\,{\rm d}V$ is the work term. x_0, y_0, z_0 are the ellipsoid solution with axial distance parameter, and T_0 is the temperature of the hot spot's center. β is the temperature exponent, and the value is 2 in this paper. The f_α[17] is the ratio of the energy deposited by alpha heating,

$$f_\alpha = 1-\frac{1}{4\phi}+\frac{1}{160\phi^3}, \quad (6)$$

$$\phi = \frac{\rho r_{\rm hs}(1+0.0082T_{\rm hs})^{1.25}}{0.025T_{\rm hs}^{1.25}}, \quad (7)$$

where ρ is the hot-spot density.

Springer *et al.*'s model needs to be improved because the DCI scheme is different from the central ignition scheme. Fast electrons heat the high-density plasma in the fast heating process, so the effect of fast electrons on the plasma must be considered. Since the time for injecting fast electrons is short, the pressure of the plasma has no time to change, and the effect of fast electrons on the pressure of high-density plasma can be neglected. Thermal conduction is a slow process, and the existence of the high-density plasma status is very short, so the effect of thermal conduction on the high-density plasma can be neglected. It is said by Betti *et al.*[18] that the rate of radiation loss is much lower than the $P{\rm d}V$ work rate when the hot-spot temperature is below 4.4 keV. The rate of alpha heating is greater than the rate of the radiation loss when the hot-spot temperature is above 4.4 keV. Therefore, the radiation loss term is also not to be considered. Combining the above considerations, the inner pressure ($P_{\rm p}$) and temperature ($T_{\rm p}$) of the high-density plasma are a function of time in the fast heating process of the DCI scheme,

$$\frac{{\rm d}P_{\rm p}}{{\rm d}t} = \frac{2}{3V}\left(Q_\alpha-\frac{5}{2}P_{\rm p}\frac{{\rm d}V}{{\rm d}t}\right), \quad (8)$$

$$\frac{{\rm d}T_{\rm p}}{{\rm d}t} = \frac{2T_{\rm p}}{3P_{\rm p}V}\left(f_\alpha Q_\alpha-P_{\rm p}\frac{{\rm d}V}{{\rm d}t}\right)+\eta Q_{\rm h}, \quad (9)$$

where $Q_{\rm h}$ is the rate of the energy deposition of fast electrons. η is the energy deposition efficiency of fast electrons. The energy deposition efficiency of fast electrons is low due to fast electron divergence, beam instability, etc. Therefore, the value of η is 25%. The article of Glinsky *et al.*[19] introduces the formula for the energy deposition of fast electrons:

$$Q_{\rm h} = \frac{8\pi}{3\sqrt{3}}\frac{n_{\rm h}e^4\ln\Lambda}{m_{\rm e}^{1/2}T_{\rm h}^{1/2}}, \quad (10)$$

where $n_{\rm h}$ and $T_{\rm h}$ are the density and temperature of fast electrons, respectively, and $\ln\Lambda$ is the usual Coulomb logarithm. e and $m_{\rm e}$ are the elementary charge and electron mass, respectively.

The $P_{\rm p}{\rm d}V$ is the work term for the high-density plasma. The volume change is caused by the collision of the two low-density plasmas and the pressure difference between the inside and outside of the high-density plasma. Since the injection time of the fast electrons is very short, the fast electrons mainly collide with the electrons in the high-density plasma, and then the heated electrons collide with the ions, which increase in temperature. In subsequent simulations, the relaxation time of electrons and ions can be quite long due to the high-temperature difference between the electrons and the ions.[20] The duration of the high-density plasma state is only 100 ps or even less, so the high-density plasma has not yet reached thermodynamic equilibrium and the effect of internal and external pressure on the volume is not considered. It is also why the effect of fast electrons on the pressure of the high-density plasma is not considered. The collision of the two low-density plasmas becomes the main factor affecting the volume.

2.2. The volume change of the high-density plasma

During the head-on collision process of the DCI scheme, two low-density plasmas collide to form the high-density plasma. Since the velocity of two low-density plasmas does not become zero immediately after the collision, the volume of the ellipsoidal high-density plasma changes. During the existence of the high-density plasma status, the two low-density plasmas continue to collide until the velocity is zero, the density of the high-density plasma increases, and the volume of the ellipsoidal high-density plasma slowly decreases. Subsequently, the two low-density plasmas move in the opposite direction due to Coulomb repulsion, the density of the high-density plasma decreases, and the volume of the ellipsoidal high-density plasma slowly expands. The change in the volume of the ellipsoidal high-density plasma can be divided into a compression process and an expansion process. Since the formation of high-density plasma is mainly affected by collision, there is no need to consider the effect of ablation. Therefore, the density of high-density plasma is inversely related to the change in volume. To simplify the model, the change in the density of the high-density plasma[13] during the existence of the high-density plasma status is

$$\rho_{\rm p} = \rho_{\rm max}-\frac{(\rho_{\rm max}-\rho_0)}{(\tau/2)^2}\left(t-\frac{\tau}{2}\right)^2, \quad (11)$$

where τ is the duration of the high-density plasma and t is a moment in time during the existence of the high-density plasma status. $\rho_{\rm max}$, ρ_0, and $\rho_{\rm p}$ are the maximum density of the high-density plasma, the initial density at the formation of the plasma state, and the plasma density at a moment in time

during the existence of the high-density plasma status, respectively. During the existence of the high-density plasma status, the faster the speed of the low-density plasma, the more rapidly the density of the high-density plasma changes, and the shorter the existence of the high-density plasma.

2.3. Numerical calculations

Equations (8), (9), and the term of Q_α are coupled to each other, which makes it difficult to obtain the analytical solution. In this subsection, the first-order time derivatives (i.e., $\mathrm{d}p_\mathrm{p}/\mathrm{d}t$, $\mathrm{d}T_\mathrm{p}/\mathrm{d}t$ and $\mathrm{d}V/\mathrm{d}t$) of Eqs. (8) and (9) are solved by the first-order backward difference. The Δt represents the time step. Equations (8) and (9) can be expressed as

$$P_\mathrm{p}^n = P_\mathrm{p}^{n-1} + \frac{\Delta t}{2\pi\left(r_\mathrm{p}^{n-1}\right)^2}\frac{Q_a^{n-1}}{r_b^{n-1}} - \frac{5}{3}\frac{\left(r_b^{n-1}-r_b^{n-2}\right)}{\left(r_b^{n-1}\right)}P_\mathrm{p}^{n-1}, \quad (12)$$

$$T_\mathrm{p}^n = T_\mathrm{p}^{n-1} + \frac{\Delta t}{2\pi}\frac{T_\mathrm{p}^{n-1}\left(f_a^{n-1}Q_a^{n-1}\right)}{P_\mathrm{p}^{n-1}\left(r_\mathrm{p}^{n-1}\right)^2 r_b^{n-1}} - \frac{2T_\mathrm{p}^{n-1}}{3}\frac{\left(r_b^{n-1}-r_b^{n-2}\right)}{\left(r_b^{n-1}\right)} + \eta Q_\mathrm{h}^{n-1}\cdot\Delta t. \quad (13)$$

The periodic boundary conditions are applied in this research. Considering the initial conditions, such as the initial temperature and initial inner pressure of the high-density plasma, the numerical solution of the linear system equation can be obtained by the iteration method.

3. Numerical simulations and discussion

Since the density of the high-density plasma varies due to the collision of two low-density plasma, the high-density plasma reaches the ignition temperature at different moments. The relationship between the ignition temperature (T_it), the density (ρ_p), and the radius (r_p) of the plasma is given by[21]

$$\rho_\mathrm{p} r_\mathrm{p} T_\mathrm{it} > 6\cdot\left(\frac{\rho_\mathrm{p}}{\rho_\mathrm{c}}\right)^{0.5}. \quad (14)$$

The ignition temperature and the actual temperature without injecting fast electrons of the high-density plasma versus time are shown in Fig. 2.

As shown in Fig. 2, the temperature of the high-density plasma changes insignificantly when the plasma is only affected by $P\mathrm{d}V$ work and alpha particles. It is difficult for the high-density plasma to reach the ignition temperature by $P\mathrm{d}V$ work alone. Therefore, the high-density plasma can be heated to the ignition temperature by injecting fast electrons.

In practical experiments, it is necessary to consider the issue of energy input from fast electrons. Due to the different ignition temperatures of the plasma at different moments, we discuss the two cases where fast electrons are injected with the minimal energy. One case is that fast electrons directly heat the high-density plasma to the ignition temperature with the minimal energy. Thus, the optimal time for injecting fast electrons is discussed in Subsection 3.1. Another case is that fast electrons with the minimal energy heat the high-density plasma to a relatively high temperature, and then the plasma can be heated to the ignition temperature by alpha particles and $P\mathrm{d}V$ work. Thus, the shortest injection time required for fast electrons with the same energy will be discussed in Subsection 3.2. The two cases are simulated by numerical simulations. In the following simulations, the high-density plasma has a length of 30 um for the long semiaxes (r_p) and 20 μm for the short semiaxes (r_b). The high-density plasma status has an initial temperature of 1 keV, which can be sustained for 100 ps. Initial pressure (P_p) of the high density plasma is 200 Gbar. The variation in the density of the high-density plasma is shown in Fig. 3.

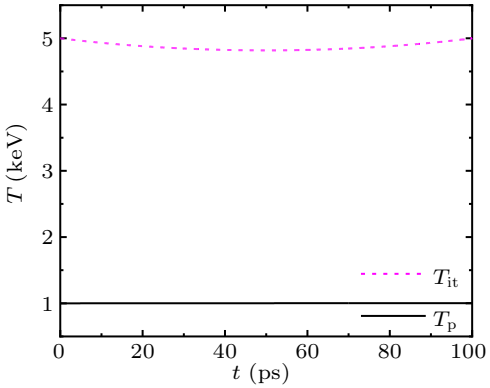


Fig. 2. The high-density plasma has an initial temperature of 1 keV, and the duration is 100 ps. The ignition temperature and the actual temperature without injecting fast electrons of the high-density plasma versus time are shown.

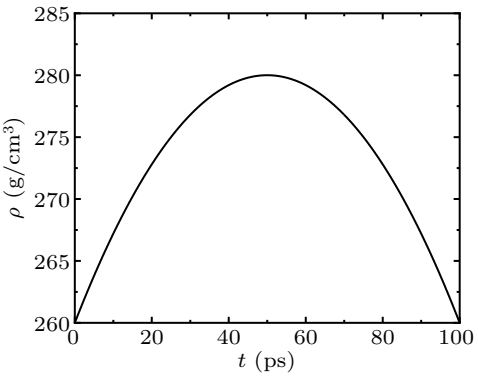


Fig. 3. The variation in the density of the high-density plasma due to collisions. The initial density (ρ_0) is 260 g/cm^3 when the high-density plasma is formed, the maximum density (ρ_max) of the high-density plasma is 280 g/cm^3.

3.1. The optimal moment for injection

When the time for injecting fast electrons is relatively long, fast electrons can directly heat the high-density plasma to the ignition temperature. In this case, the optimal moment of injecting fast electrons is worthwhile to study when fast electrons with the minimal energy heat the plasma to the ignition temperature. To explore the optimal moment of injecting fast electrons, fast electrons with a temperature of 100 keV[19] and

a density of 1.0×10^{22} g/cm^3 are injected into the high-density plasma at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps) during the existence of the high-density plasma status. During the process of the plasma being heated to the ignition temperature, the temperature of the high-density plasma versus the time when fast electrons are injected at different moments, as shown in Fig. 4(a). The time for fast electrons to heat the plasma to the ignition temperature is shown in Fig. 4(b), when fast electrons are injected at different moments. In our model, we also consider that alpha particles and $P\mathrm{d}V$ work affect the temperature of the high-density plasma. To explore the effect of alpha particles, $P\mathrm{d}V$ work, and fast electrons on the temperature of high-density plasma, we plotted the heating rate of alpha particles, $P\mathrm{d}V$ work, and fast electrons, as shown in Fig. 4(c).

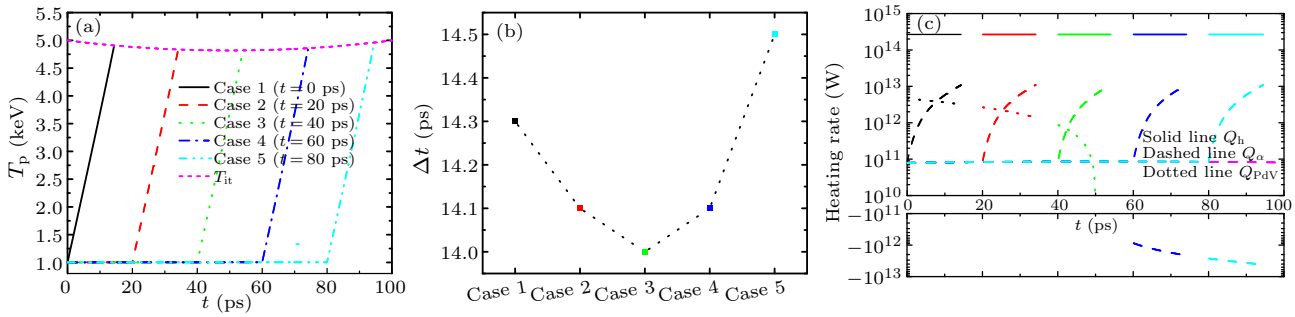


Fig. 4. (a) During the process of the plasma reaching the ignition temperature, the temperature of high-density plasma versus time when fast electrons are injected at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). (b) The shortest injection time for fast electrons to heat the plasma to ignition temperature is shown when fast electrons are injected at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). (c) The heating rate of alpha particles, $P\mathrm{d}V$ work, and fast electrons versus time are shown when fast electrons are injected at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). Solid, dashed, and dotted lines indicate the heating rates for fast electrons, alpha particles, and $P\mathrm{d}V$ work, respectively. The magenta dashed line is the heating rate of the alpha particle without injecting fast electrons.

The magenta line is the ignition temperature of the high-density plasma at the different moments in Fig. 4(a). As shown in Fig. 4(a), the temperature of the high-density plasma rises rapidly to the ignition temperature when hot electrons are injected. As can be seen in Fig. 4(c), the heating rate of hot electrons is much higher than that of alpha particles and $P\mathrm{d}V$ work. Hot electrons are injected with the same energy, which heats the high-density plasma with approximately the same heating rate. Therefore, the trends of temperature changes in the high-density plasma are roughly the same.

As shown in Figs. 4(a) and 4(b), the time for fast electrons to heat the plasma to the ignition temperature is the shortest when injecting fast electrons near the maximum density of the plasma. In this case, fast electrons consume the minimal energy. Combined with Figs. 2 and 4(c), we can analyze why injecting fast electrons near the maximum density in high-density plasma requires the minimal energy. When the high-density plasma reaches the ignition condition at its maximum density, the ignition temperature of the plasma and the energy required for the ignition are the lowest. Although it can be seen from Fig. 4(c) that the heating rate of the $P\mathrm{d}V$ work decreases when the density of the high-density plasma reaches its maximum, the heating rate of fast electrons is much larger than that of the $P\mathrm{d}V$ work and alpha particles. When the energy required for the high-density plasma to reach the ignition temperature is reduced, the time for fast electrons with the same heating rate to heat the plasma is reduced. Therefore, the optimal moment of injecting fast electrons to heat the plasma to the ignition temperature is near the maximum density of the high-density plasma during the existence of the high-density plasma status. In experiments, it is considered to inject fast electrons near the maximum density of the high-density plasma to reduce the injection energy of fast electrons.

It is also found in Fig. 4(c) that the heating rate of alpha particles increases when fast electrons are injected into the high-density plasma. The reason is not difficult to analyze. When the temperature of the high-density plasma increases, the number of alpha particles produced by the high-density plasma also increases, and the heating rate of alpha particles is bound to increase.

3.2. The shortest injection time

In the previous case, we also found an effect of alpha particles on the temperature of the high-density plasma when the temperature of the high-density plasma is increased. When the time for injecting fast electrons is limited, or the efficiency for energy deposition of fast electrons is low, fast electrons may not be able to heat the plasma directly to the ignition temperature. In this case, it is considered that injecting fast electrons for a short time would heat the high-density plasma to a relatively high temperature. Then, alpha particles with a high heating rate and $P\mathrm{d}V$ work heat the plasma to the ignition temperature. Therefore, it is worth studying when injecting fast electrons with the minimal energy to make the high-density plasma reach the ignition temperature during the persistence of the high-density plasma status. In order to study injecting fast electrons with the minimal energy, we can study the shortest injection time of fast electrons when the injected fast electrons

have the same energy. Since the density and the volume of the high-density plasma change, we divided it into two cases to study the shortest injection time for fast electrons to make the high-density plasma reach the ignition temperature. The first case is that the plasma reaches the ignition temperature (4.82 keV) at the end of the compression, where the plasma has the highest density. The second case is that the plasma reaches the ignition temperature (5 keV) at the end of the expansion, where the plasma has the lowest density.

3.2.1. Compression process

In order to study when injecting fast electrons takes the shortest time, fast electrons are injected into the high-density plasma at different moments during the compression process. The temperature of the high-density plasma with time and the shortest injected time for fast electrons at different moments (0 ps, 10 ps, 20 ps, 30 ps, and 40 ps) are shown in Figs. 5(a) and 5(b), respectively. In this subsection, the high-density plasma is heated to the ignition temperature at the end of the compression process. Therefore, the heating rate of the $P\mathrm{d}V$ work is the same throughout the compression process regardless of injecting fast electrons at any moment. We mainly analyze the effect of the heating rate of alpha particles on the high-density plasma, and the rate of alpha heating versus time is shown in Fig. 5(c). The injected fast electrons have a temperature of 100 keV and a density of 1.0×10^{22} g/cm^3.

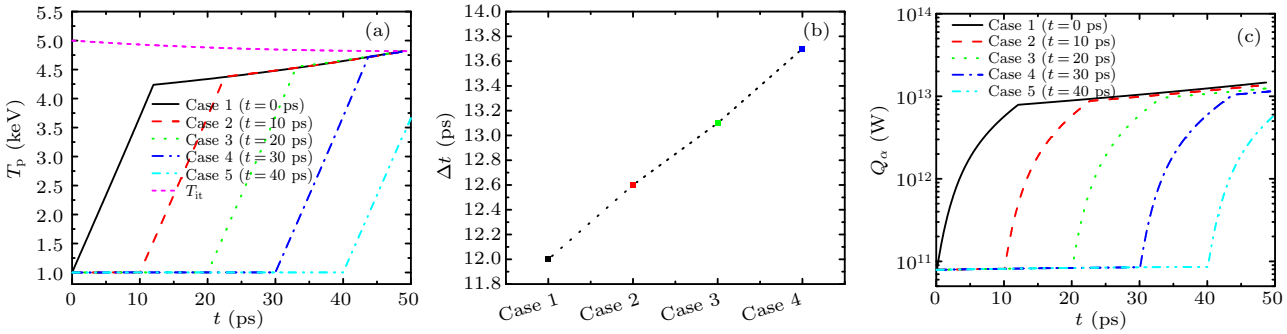


Fig. 5. (a) During the compression process, the temperature of the high-density plasma versus time when fast electrons are injected at different moments (0 ps, 10 ps, 20 ps, 30 ps, and 40 ps). (b) The shortest injection time required for fast electrons to heat the plasma is shown when injecting fast electrons at different moments (0 ps, 10 ps, 20 ps, 30 ps, and 40 ps). Since the plasma injected with fast electrons at 40 ps did not reach the ignition temperature, it was not used for comparison. (c) The variation of the heating rate of alpha particles with time is shown when injecting fast electrons at different moments (0 ps, 10 ps, 20 ps, 30 ps, and 40 ps).

As seen from Fig. 5(a), except for injecting fast electrons at 40 ps, the high-density plasma at the density maximum can be heated to the ignition temperature by fast electrons and alpha particles at other injection moments. As seen from Fig. 5(b), the injected time required for fast electrons to heat the high-density plasma to the ignition temperature is the shortest when injecting fast electrons at 0 ps. Moreover, the later fast electrons are injected during the compression process, the longer the necessary time to inject the fast electrons. Therefore, the moment of injecting fast electrons with the shortest time should be at the beginning of the compression, when the plasma reaches the ignition temperature at the maximum density. Combined with Fig. 5(c), we can explain with this phenomenon why injecting fast electrons takes the shortest injection time at the beginning of the compression. When fast electrons are injected, it can be seen that the heating rate of the alpha particles rises rapidly. The rate of alpha heating when injecting fast electrons at 0 ps is faster than the rate of alpha heating without injecting fast electrons at 0 ps. Thus, the high-power alpha particles can heat the plasma injected with fast electrons at 0 ps for a longer time, and the time required for injecting fast electrons is the shortest. When the time for injecting fast electrons is limited, or the efficiency for energy deposition of fast electrons is low, we consider injecting fast electrons at the beginning of the compression. The energy required for fast electrons is the least when injecting fast electrons at this time.

When fast electrons' density and temperature change, it is worth studying how the shortest injected time required for fast electrons changes. The shortest injected time required for fast electrons with different temperatures and densities is shown in Figs. 6(a) and 6(b), respectively, when the plasma reaches the ignition temperature during the compression process.

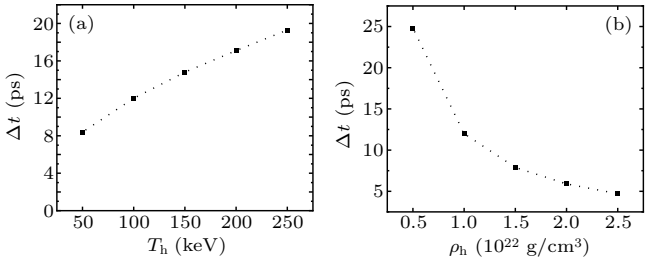


Fig. 6. The shortest injected time required for fast electrons with different temperatures (a) and densities (b) is shown, when the plasma reaches the ignition temperature during the compression process. In (a), fast electrons are injected at the beginning of the compression, all of which have the same density of 1.0×10^{22} g/cm^3 and temperatures of 50 keV, 100 keV, 150 keV, 200 keV, and 250 keV. In (b), fast electrons are injected at the beginning of the compression, all of which have the same temperature of 100 keV and a density of 0.5×10^{22} g/cm^3, 1.0×10^{22} g/cm^3, 1.5×10^{22} g/cm^3, 2.0×10^{22} g/cm^3, and 2.5×10^{22} g/cm^3.

As seen from Fig. 6(a), the shortest injected time required

for fast electrons increases when the temperature of fast electrons increases. This result is consistent with the physical laws of fast electron heating because the energy deposition efficiency of fast electrons decreases when the temperature of fast electrons increases. As seen from Fig. 6(b), the shortest injected time required for fast electrons is shortened when the density of fast electrons increases. It is not difficult to analyze the reasons for this phenomenon. When the densities of fast electrons increase, the frequency of collisions between fast electrons and the high-density plasma also increases. Therefore, the time and energy required for injecting fast electrons can be further reduced by decreasing the temperature appropriately and increasing the density of fast electrons.

3.2.2. Expansion process

In order to study when injecting fast electrons takes the shortest time, which makes the plasma reach the ignition temperature at the end of the expansion, fast electrons are injected with the necessary time at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). The images of the temperature of the high-density plasma versus time and the injected time required for fast electrons are shown in Figs. 7(a) and 7(b), respectively, when injecting fast electrons at different moments. In order to study the effect of alpha particles on the temperature of the high-density plasma, the image of the heating rate of alpha particles versus time is shown in Fig. 7(c). The injected fast electrons have a temperature of 100 keV and a density of 1.0×10^{22} g/cm^3.

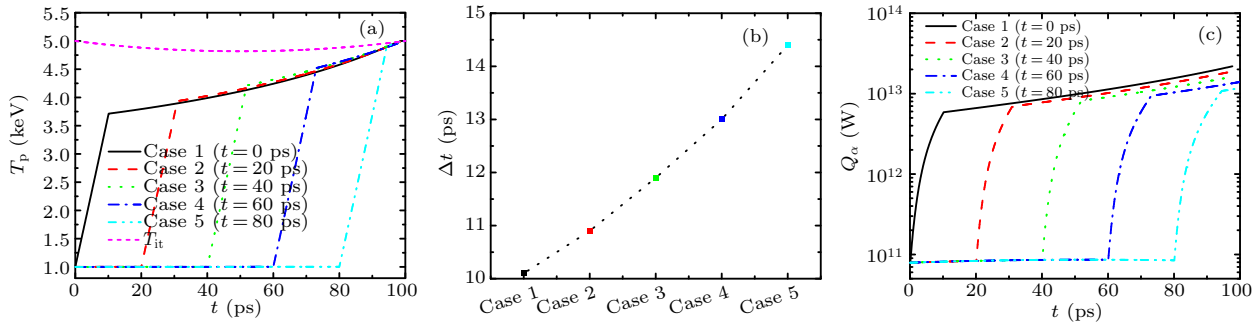


Fig. 7. (a) During the persistence of the high-density plasma status, the temperature of the high-density plasma versus time with fast electrons injected at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). (b) The shortest injection time required for fast electrons to heat the plasma is shown when fast electrons are injected at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps). (c) The variation of the heating rate of alpha particles with time is shown, when injecting fast electrons at different moments (0 ps, 20 ps, 40 ps, 60 ps, and 80 ps).

It can be seen from Figs. 7(a) and 7(b) that, as in the case of the compression process, injecting fast electrons with the shortest time is still at the beginning of the compression when the plasma reaches the ignition temperature at the end of the expansion. The later that fast electrons are injected during the existence of the high-density plasma status, the longer the necessary time to inject the fast electrons. Combined with Fig. 7(c), it is clear that the cause of this phenomenon is the same as in the previous case. The rate of alpha heating when injecting fast electrons at 0 ps is faster than the rate of alpha heating without injecting fast electrons at 0 ps, and the higher heating rate of alpha particles heats the plasmas for a longer time. Therefore, the moment of injecting fast electrons with the shortest time is at the beginning of the compression, which allows the plasma to reach the ignition temperature at the end of the existence of the high-density plasma status. Meanwhile, fast electrons require the minimal energy to be injected.

The shortest injection time required for fast electrons with different temperatures and densities is shown in Figs. 8(a) and 8(b), respectively, when the plasma reaches the ignition temperature during the existence of the high-density plasma status.

As seen from Figs. 8(a) and 8(b), the effect of the density and temperature variation of injected fast electrons on the shortest injection time is the same as in the previous case. The time and energy required for injecting fast electrons can be further reduced by decreasing the temperature appropriately and increasing the density of the fast electrons.

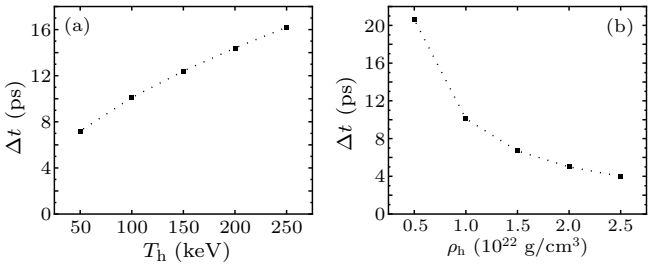


Fig. 8. The shortest injected time required for fast electrons with different temperatures (a) and densities (b) is shown, when the plasma reaches the ignition temperature during the existence of the high-density plasma status. In (a), fast electrons are injected at the beginning of the compression, all of which have the same density of 1.0×10^{22} g/cm^3 and a temperature of 50 keV, 100 keV, 150 keV, 200 keV, and 250 keV. In (b), fast electrons are injected at the beginning of the compression, all of which have the same temperature of 100 keV and a density of 0.5×10^{22} g/cm^3, 1.0×10^{22} g/cm^3, 1.5×10^{22} g/cm^3, 2.0×10^{22} g/cm^3, and 2.5×10^{22} g/cm^3.

In the experiment, due to the low energy deposition efficiency of fast electrons, it can be considered that fast electrons are first injected for a short time to heat the high-density plasma. Subsequently, the high-density plasma is heated to

the ignition temperature by alpha particles produced by the high-density plasma. This method could effectively reduce the required injected energy of fast electrons. From the analysis above, it can be seen that injecting fast electrons at the beginning of the compression process requires minimal injected energy.

3.3. Comparison

A comparison of the shortest injected time required for fast electrons at different moments (0 ps, 10 ps, 20 ps, and 30 ps) between the compression and expansion processes is given. The temperature of the high-density plasma with time, the shortest injection time required for fast electrons, and the heating rate of the alpha particles with time are shown in Figs. 9(a), 9(b), and 9(c), respectively.

As seen from Fig. 9(a), the time for the high-density plasma to reach the ignition temperature in the compression process is earlier than in the expansion process, and the ignition temperature of the plasma in the compression process is lower than in the expansion process. As seen from Fig. 9(b), the shortest injected time required for fast electrons in the compression process is longer than in the expansion process at the same injected moments. Combined with Fig. 9(c), the reason for this phenomenon is that the plasma is heated by the alpha particles with high heating rates for a longer time when the plasma reaches the ignition temperature during the expansion process. As a result, fast electrons are injected for a shorter time when the plasma reaches the ignition temperature during the expansion process.

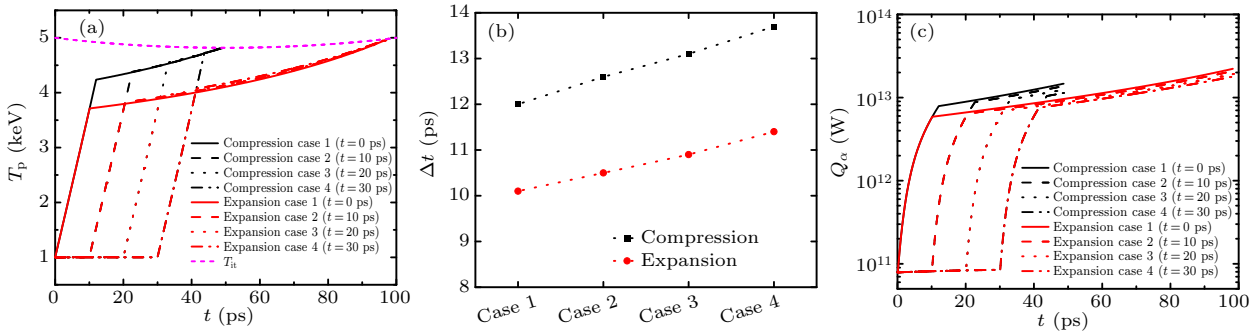


Fig. 9. Comparison of the temperature of the high-density plasma (a), the injection time required for fast electrons (b), and the heating rate of the alpha particles (c) between the compression and expansion processes.

By comparing the compression and expansion processes, we get some conclusions. When the high-density plasma reaches the ignition temperature at the end of compression, the time required for the plasma to reach the ignition temperature is short. However, the shortest injection time required for fast electrons in the compression process is longer than in the expansion process. The energy required for injecting fast electrons is also relatively high. When the high-density plasma reaches the ignition temperature at the end of the expansion, the injection time required for fast electrons is shorter than in the compression process. However, the plasma takes the longest time to reach ignition temperature.

4. Conclusion

In this article, we have proposed a model for the variations in the temperature and inner pressure of the high-density plasma when fast electrons are injected into high-density plasma in the fast heating process. Due to the effect of the collision of the two low-density plasma, the density and volume of the high-density plasma vary. The change in volume of the ellipsoidal high-density plasma is divided into a compression process and an expansion process. According to the Lawson criterion, the ignition temperature of the high-density plasma changes at different moments when the density of the plasma changes. Therefore, the energy required for the high-density plasma to reach the ignition temperature is different, and the time for fast electrons to be injected at different moments to heat the high-density plasma to the ignition temperature is different. When injecting fast electrons is relatively long, fast electrons can directly heat the high-density plasma to the ignition temperature. The optimal moment of injecting fast electrons is near the plasma density maximum because the plasma has the lowest ignition temperature and the lowest energy required for ignition at this time. When the time for injecting fast electrons is limited, or the efficiency for energy deposition of fast electrons is low, fast electrons may not be able to heat the plasma directly to the ignition temperature. In order to reduce the injection duration and energy inputs of fast electrons, we can consider injecting fast electrons for a short time to heat the plasma to a relatively high temperature, and the plasma continues to be heated to the ignition temperature by alpha particles with the high heating rate and $P\mathrm{d}V$ work. By numerical simulations, it is obtained that fast electrons should be injected at the beginning of the compression when fast electrons need to be injected for the shortest time and the minimal energy. Because the heating rate of alpha particles is faster when fast electrons are injected at the beginning of the compression than when no fast electrons are injected

at the beginning of compression, alpha particles with a high heating rate can heat the plasma for a longer time and the time required for injecting fast electrons is the shortest. Moreover, it is found that increasing the density of fast electrons can further shorten the injected time of fast electrons.

Acknowledgements

Project supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA25051000), the National Key R&D Program of China (Grant No. 2023YFA1608400), the National Natural Science Foundation of China (Grant No. 12005008), and the Natural Science Foundation of Top Talent of SZTU (Grant No. GDRC202209).

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