Simulation Study of the Multi-Species Ion Plasma Interacting with an Ultra Intense Laser

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Abstract
By the recent development of laser technology, the laser irradiation intensity can be well above $10^{18}$ W/cm². The simulation of ultra intense laser interaction with solid density plasmas are presented in this paper. Fast ion and electron emission, neutron yield due to D-D reaction and absorption of laser energy are discussed.

Keywords: particle simulation, ultra intense laser, dense plasma, fast ignitor, collisionless shock wave, particle acceleration, D-D reaction, neutron emission,

1. INTRODUCTION

The development of short-pulse high intensity lasers has opened new regime in the study of laser produced plasmas. At intensities higher than $10^{19}$ W/cm², the electron quiver velocity for 1 μm radiation becomes relativistic and the radiation pressure reaches more than 300 Mbar. In this regime, generation of fast particle [1, 2] and MeV hard X-ray [3] have been predicted. It has been proposed recently by Tabak et al. [4] to use these high energy particles for inertial confinement fusion, which is called fast ignitor. The fast ignitor concept could drastically change the ignition requirement for inertial confinement fusion program. In the fast ignitor scheme, a short intense laser is injected at the time around the maximum compression and additional heating on the compressed core by the energetic particles follows.

In the fast ignitor, the energetic particles are used to heat the fuel and to start thermonuclear reaction. The energetic particle accelerated by the intense laser has the energy above a few hundreds keV. Therefore, another possibility of fusion reaction is revealed. If the deuteron contained in the fuel gets energy above 100 keV, it will react with another deuteron. This direct D-D reaction will assist the thermonuclear burning.

Recently, it was reported that the fast ion up to MeV are created in picosecond laser produced plasma [5]. Then, fusion yields and neutron emissions were measured from deuterated polystyrene targets irradiated with focused intensity of above $10^{18}$ W/cm². The fusion yield was $4.4 \times 10^9$.

In this paper, we investigate the fast ion generation mechanisms by 1-2/2 D particle simulation and clarify the energy particular of absorbed laser intensity between energetic electron and ion. Then the neutron yield by D-D reaction is discussed. In section 2, the simulation conditions are described. In section 3 and 4, the acceleration of energetic particles and neutron yield are discussed. Section 5 is devoted to discuss the energy conversion efficiency. A summary of the results is given in section 6.
2. SIMULATION CONDITIONS

We performed simulations using a one dimensional fully relativistic electro-magnetic particle in cell (PIC) code. In this code, a particle has one space component and three velocity components, and all fields have three dimensional components. In this code, to take account of a real plasma conditions, three species of particle, electron, deuteron and carbon are included and real mass ratios are taken.

Our simulation system is as follows; the plasma which thickness is \( L_p \) is situated at the center of the system and vacuums of length \( L_{+} \) in each side of the plasma to avoid the influences of the boundary. Each of the simulation runs is up to about 0.16 psec, so that very few particles reach to the system boundary. Laser light is injected from one side of the system at a constant intensity through a run. Simulation parameters are given in Table 1. The wide range of intensity \( I_L = 6.3 \times 10^{19} - 6.3 \times 10^{22} \) W/cm² for 1.06 \( \mu \)m laser light are investigated. The ratio of electron density \( n_e \) to critical density \( n_c \) is 300, which is equivalent to 1 g/cm² of deuterated polystyrene (C₈D₈). The temperature of electron \( T_e \) and ion \( T_i \) are the same. The electron temperature must be chosen to satisfy the condition \( 2I_L/c > P_i \), where \( I_L \) is laser intensity, \( c \) the velocity of light and \( P_i \) the initial pressure of the plasma. If the condition was not satisfied, no particle acceleration occurs. In the case of relatively low intensities (1 - 3), initial temperature is set to 1.5 keV and high intensity case (4 - 7) 25 keV. In either case, the temperatures are chosen relatively high for the convenience of simulations. But there are no significant influences to the particle acceleration as long as the condition \( 2I_L/c > P_i \) is filled. In these simulations, the number of spatial grids \( N_x \) is \( N_x = 8192 \). The grid spacing equals Debye length. The total number of super particles are given in Table 1, which means that \( 3 \times 100 \) particles per one cell are used.

3. ELECTRON AND ION ACCELERATION

When the laser is injected, by the radiation pressure, electrons are pushed into the plasma from the surface. But ions are almost fixed because of its inertia. Therefore strong electrostatic field due to the charge separation is induced and ions are accelerated by the electrostatic force. This process mainly takes place at the laser-plasma interface. In Figure 1, the simulation results for the intensity \( 6.3 \times 10^{19} \) W/cm² are shown. The laser accelerates both electrons and ions. In the figure, laser is injected from left side, so that the plasma is pushed to right and compressed by the piston action of the radiation pressure [Fig. 1 (a), (b)]. From the carbon and deuteron phase plot [Fig. 1 (c), (d)], it is clearly seen that a shock wave is formed and ions are reflected at the shock front \( (\theta/c = 30.5) \). The reflection of ion is due to the jump of potential at the shock front. The ions in the upstream of the shock mainly flow into the downstream. But, owing to the thermal energy spread, a part of ion can not pass through the potential barrier so that it is reflected. The behavior of deuteron and carbon are essentially the same because the charge to mass ratio of each particles are equivalent. However, the differences appear in the density profile and phase plot. Since the deuteron thermal energy spread is wider than carbon, more deuteron ions are reflected at the shock front than carbon [Fig. 1 (c), (d)]. Consequently, the deuteron density in the upstream of the shock is lowered [Fig. 1 (b)].

In hydrodynamic shock wave, collisions are dominant. Shock wave also exist in plasma, even when there are no collisions [6]. The typical potential structure in the shock is shown in Figure 2. According to the potential, ions are reflected at the shock front. The reflection of ions due to the electro-static potential leads to the formation of collisionless shock wave.

We now discuss theoretically the collisionless shock structure and the ion acceleration mechanism. In

<table>
<thead>
<tr>
<th>( I_L ) (W/cm²)</th>
<th>( \omega_p L_p/c )</th>
<th>( \omega_p L_p/c )</th>
<th>( N_x )</th>
<th>( N_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( \times 10^{19} )</td>
<td>13.1 ( (= 2.1 \mu m) )</td>
<td>29.6 ( (= 5 \mu m) )</td>
<td>8192</td>
<td>( 3 \times 150000 )</td>
</tr>
<tr>
<td>2 ( \times 10^{20} )</td>
<td>25</td>
<td>36.2 ( (= 6.1 \mu m) )</td>
<td>130 ( (= 22 \mu m) )</td>
<td>( 3 \times 100000 )</td>
</tr>
</tbody>
</table>
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Fig. 1 Simulation results for $I_0 = 6.3 \times 10^{19}$ W/cm², $\omega_0 t = 258$: (a) density and potential profile of electron; (b) density profile of carbon and deuteron; (c, d) phase space plots of carbon (c) and deuteron (d). Density is normalized by initial value of each species. Laser is injected from left side so that the plasma is pushed to right and compressed. From ion phase plot (c, d), it is clearly seen that a shock wave is formed and ions are reflected at the shock front.

Fig. 2 Acceleration mechanism of high energy ion. Laser is irradiated from left side of plasma. The laser ponderomotive force generate shock wave due to the ion and electron acceleration. This shock wave is accompanied with an electrostatic potential, which kicks the ions at the front of the shock.
Figure 2, $P_s, P_o$, $\rho_s, P_o$ and $\rho_o$ represent the laser radiation pressure, the pressure and mass density after the shock and those of the background and $v_s$ is the shock velocity. In the frame moving with the shock front, plasma flow velocity is $v - v_s$ in the down-stream of the shock and $-v_s$ in the up-stream. In this frame, conservation laws of mass, momentum and energy are described as follows,

$$\rho_o v_s = \rho_s (v_s - v)$$  \hspace{1cm} (1)

$$P_o + \rho_o v_s^2 = P_s + \rho_s (v_s - v)^2,$$  \hspace{1cm} (2)

$$\frac{k}{\kappa - 1} P_o v_s + \frac{1}{2} \rho_o v_s^3 = \frac{k}{\kappa - 1} P_s (v_s - v)$$  \hspace{1cm} (3)

where the relation $P_s = P_o$ is assumed and $\kappa$ is the specific heat ratio, note that $\kappa = 3$ for collisionless ideal gas. From these three equations $\rho_s, v_s$ and $v$ are determined, as follows

$$k = \frac{\rho_o / \rho_s}{1 - (\kappa + 1)} P_s / P_o, \quad (\kappa - 1) = 2$$  \hspace{1cm} (4)

$$\frac{v_s}{c_s} = \sqrt{\frac{P_s / P_o - 1}{1 - 1/k}}$$  \hspace{1cm} (5)

and

$$\frac{v}{c_s} = \sqrt{(1 - 1/k)(P_s / P_o - 1)},$$  \hspace{1cm} (6)

where $c_s = \sqrt{P_s / \rho_o}$ is the sound speed. In the limit of $P_s / P_o \gg 1$, eq. (4) becomes $k = \rho_o / \rho_s = (\kappa + 1) / (\kappa - 1) = 2$ for $\kappa = 3$. This compression ratio agrees well with that of the 1D PIC simulations for various laser intensities.

The electrostatic potential in the shock, $\phi$ is described by the following equations [6],

$$\frac{d^2 \chi}{d \xi^2} = - \frac{d V(\chi)}{d \chi},$$  \hspace{1cm} (7)

$$V(\chi) = 1 - e^\chi - \frac{m^2}{2} \left( 1 + \sqrt{1 - \frac{2 \chi}{m^2}} \right)^2,$$  \hspace{1cm} (8)

where $\xi, \mu$ and $\chi$ are defined by $\xi = x / \lambda_D$, $m = \mu / c_s$ and $\chi = Z \phi / T_e$ (x is the coordinates, $\lambda_D$ is Debye length, $Z$ and $e$ are charge number and elemental charge, $T_e$ is electron temperature). For the collisionless shock wave, the electrostatic potential $\phi$ approaches to a constant value $\phi_{\infty}$. When $x \to -\infty$, $d^2 \chi / d \xi^2 \to 0$, that is

$$- \frac{d V(\chi)}{d \chi} = e^\chi - \frac{1}{\sqrt{1 - \frac{2 \chi}{m^2}}} \to 0.$$  \hspace{1cm} (9)

When $m^2 \gg 1$, non zero solution of Eq. (9) is very close to $\chi_{\infty} = m^2 / 2$ for $x \to -\infty$, $m$ is the Mach number of the shock wave and one can realize that the condition $m^2 \gg 1$ is filled in the limit of $P_s / P_o \gg 1$ from Eq. (5). Here we put $\chi_{\infty} = m^2 / 2 + \delta$ where $\delta$ is a small number and substitute it into the Eq. (9). Expanding the exponential then we get

$$\delta = \frac{m^2}{2} e^{-m^2},$$  \hspace{1cm} (10)

We define the critical velocity $v_c$ by

$$\frac{1}{2} M_i v_c^2 = Z e \phi,$$  \hspace{1cm} (11)

or

$$v_c = \sqrt{2 \chi / c_s},$$  \hspace{1cm} (12)

where $M_i$ is the mass of ion. In Figure 2, at the front of shock wave ion runs toward the shock front. If the ion velocity is smaller than $v_c$, the ion is reflected due to the potential barrier. In the laboratory frame, it is seen that reflected ions are accelerated to high energy. The kinetic energy of the ion $E_i$ is

$$E_i = \frac{1}{2} M_i (v_s + v)^2.$$  \hspace{1cm} (13)

From equations (10), (12) and (13), we obtain

$$E_i = \frac{1}{2} M_i c_s^2 \left( 1 + \sqrt{1 - e^{-m^2}} \right)^2.$$  \hspace{1cm} (14)

Here, $m = v_c / c_s$ is calculated from Eq. (5) as the function of laser intensity. In the case that there are species of ion more than two in the plasma, Eq. (12) is modified as

$$v_c = \sqrt{\frac{2 \chi M Z}{M Z c_s}},$$  \hspace{1cm} (15)

where $M$ and $Z$ are averaged mass and charge number of plasma, and $M_i$ and $Z_i$ those of the aimed species.
Therefore the formula (14) becomes

\[ E_i = \frac{1}{2} M_i c^2 = \frac{1}{2} M_i c^2 \left( 1 + \sqrt{1 - \frac{M_i c^2}{M_i c^2}} \right)^2. \] (16)

In our case, because the charge to mass ratio of deuterion and carbon are equivalent, Eqs. (15) and (16) are reduced to Eqs. (12) and (14). In the limit of \( P_i/P_o \gg 1 \), we get a simple formula

\[ E_i = \frac{1}{2} M_i c^2 = 8 P_i/P_o. \] (17)

In Figure 3, shown are the electron, deuteron and carbon energy distribution functions at \( t = 0.16 \) psec for the laser intensity \( 6.3 \times 10^{19} \) W/cm\(^2\) and \( 10^{20} \) W/cm\(^2\). Horizontal axis is a normalized energy by the rest mass of each particles \( \gamma - 1 \), where \( \gamma = (1 - v^2/c^2)^{-1/2} \). From the electron distribution, Fig. 3 (a), there are hot electrons with effective temperature 2 MeV due to the \( v \times B \) heating [7]. Even for normal incidence, a very strong, high frequency longitudinal electric field is induced in the plasma at the vacuum plasma interface. This field has both the static and the oscillating component. Electrons are accelerated into the plasma by the ponderomotive force [7, 8]. Then plasma is heated up by the accelerated electrons.

In the Figs. 3 (b), (c) it is found that the maximum energy of deuteron and carbon are accelerated up to \( \gamma - 1 = 2.5 \times 10^{-4} \). As illustrated in the figures, ion energy distribution functions have three peaks. For example, in carbon distribution for \( I_L = 6.3 \times 10^{19} \) W/cm\(^2\) (Fig. 3 (b), solid line), first peak appears around \( \gamma - 1 = 0 \), which corresponds to the initial Maxwell distribution. The second and third peak appear around \( \gamma - 1 = 1 \times 10^{-5} \) and \( \gamma - 1 = 6 \times 10^{-5} \). The second and third peak correspond to ions accelerated by the laser ponderomotive force and those reflected by the shock potential respectively. Comparing the deuteron and carbon distributions, the width of the peaks are wider in the case of deuteron than carbon. This is due to the differences of thermal velocity of particles. The energy of reflected ion shifts to higher energy as the laser intensity increases. The reflected average deuterons energy, which is measured as the central energy of the peak, is plotted in Figure 4, as a function of the laser photon pressure. In the figure, analytical formula (14) is also plotted. It shows a nice agreement with each other.

The hot ions are strongly collimated forward as shown in the angular velocity distribution, Fig. 5. However, low energy component widely spread. In the

![Fig. 3](image-url)

**Fig. 3** Energy distribution function of electron (a), carbon (b) and deuteron (c) at \( \omega_o t = 283.5 \) (0.16 psec). Laser intensity is \( 6.3 \times 10^{19} \) W/cm\(^2\) (solid line) and \( 1 \times 10^{20} \) W/cm\(^2\) (dotted line). Energy (horizontal axis) is normalized by the rest energy of the each particles.
4. NEUTRON YIELD

When an ultra intense laser irradiates a plasma, collimated hot deuterium ion beams are produced. These deuterons travel into a plasma and decelerate due to collision with electrons. Then it reacts with other deuterons. We consider the total probability that one deuteron reacts with another deuteron until stops. This probability is evaluated by,

\[ p(E_\text{f}) = n_D \int_{E_\text{i}}^{E_\text{f}} v_i \sigma_{DD}(E_i) \frac{dt}{dE_i} dE_i. \]  

where \( E_\text{f} \) is energy of accelerated deuteron, \( dE_i/dt = -v_i E_i \) \( v_i \) is electron-deuteron collision frequency. \( \sigma_{DD}(E_i) \) is a cross section of the reaction \( D + D \rightarrow \text{He}^3 + n \) as a function of \( E_i \) and fitted by the formula found in reference [9].

figure, the laser incidence direction is taken to be the \( x \)-axis, and \( \theta \) is the direction of particle velocity measured from the \( x \)-axis, namely \( \theta = \tan^{-1}[(v_y^2 + v_z^2)^{1/2}/v_x] \). Note that the directivity may not be so strong in the case of 2-D or 3-D calculation because of the distortion of the vacuum-plasma interface.

![Graph showing the intensity dependence of peak energy of reflected deuteron. Results of simulation (circles) and analytical formula (14) (solid line) are plotted, where \( P^* \) is laser photon pressure \( P^* = 2k/c \), \( P_0 \) the initial plasma pressure \( P_0 = M_0 T_0 \) and \( c_s = (T_0/M)^{1/2} \).](image1)

![Graph showing the distribution of deuteron angular with respect to the \( x \)-axis (laser propagation direction).](image2)

![Graph showing the dependence of areal fusion reaction density on laser intensity (a) and pulse width (b).](image3)
To get the total neutron yield, the deuteron distribution function determined from simulation is multiplied by \( p(E) \), and integrated over energy. The result is shown in Fig. 6. Fig. 6 (a) shows a laser intensity dependence. As the laser intensity increases, neutron yield increases as was expected. Each simulation run has been performed up to 0.16 psec. Fig. 6 (b) shows a dependence of neutron yield with laser pulse width. The plots are extrapolated to 1 psec. From this figure we can expect that the neutron yield will become the order of \( 10^{17} \) m\(^{-2}\) in the case of \( I_l = 6.3 \times 10^{19} \) W/cm\(^2\), 1 psec irradiation. Assuming that laser focal area is \( 10^{-8} \) m\(^2\), we get the neutron yield \( \approx 10^9 \). This estimate is consistent with the experiment by Few et al. [5].

### 5. LASER ENERGY ABSORPTION

Laser energy conversion ratio to particle kinetic energy is plotted in Fig. 7 at the intensity from \( 6.3 \times 10^{19} \) W/cm\(^2\) to \( 6.3 \times 10^{21} \) W/cm\(^2\). The vertical axis is the ratio of the total increase of electron or ion kinetic energy to laser energy at 0.16 psec. When the intensity is low, laser energy is converted mainly to electron. But, when the laser intensity increases, the fraction of the ion energy increases. And the total absorption efficiency is the order of 10% at any laser intensity.

![Energy partitions for electron (circle), carbon (diamond) and deuteron (triangle). Solid circles represent the total absorption ratio. Laser intensities from \( 6.3 \times 10^{19} \) to \( 6.3 \times 10^{21} \) W/cm\(^2\) are investigated.](image)

### 6. SUMMARY

We performed a series of computer simulation. As the result of the simulation, fast ion and electron accelerations were measured. The fusion yield is explained by the reaction between fast deuteron accelerated by an intense laser and low energy bulk deuteron. Finally, observed laser energy on the surface of the solid density plasma was obtained by the simulation, and the absorption efficiency was the order of 10% for the intensities \( 6.3 \times 10^{19} \) W/cm\(^2\) \( \sim \) \( 6.3 \times 10^{21} \) W/cm\(^2\).

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### REFERENCES