High energy electron transport in dense plasma in fast ignition scenario

P Y Ye, Y Danno, S Ohkubo and K Nishihara
Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan
E-mail: pyye@ile.osaka-u.ac.jp

Abstract. We investigate the high energy electron transport in dense plasma for different laser intensity by using 3D PIC (Three-Dimensional Particle-In-Cell) simulation. We have observed dependence of electron energy flux on incident laser intensity. The electron energy fluxes normalized by the incident laser flux, \( \frac{I}{I_0} \), become \( \approx 0.2 \) for the normalized laser electric field of \( a = 3 \), \( \approx 0.1 \) for \( a = 1 \) and no visible flux for \( a = 0.2 \) in dense plasma region, where \( a = \frac{eE}{m_e\omega_0c} \). For the case of \( a = 3 \), we investigated space and time resolved velocity distribution functions and induced longitudinal electric field. We show that the high energy electrons have beam-like velocity distribution with relativistic thermal spread near the energy flux front. We also discuss the electromagnetic instabilities associated with the high energy electron beam taking the relativistic thermal spread of the beam into account.

1. Introduction
The fast ignition laser fusion involves in transport of high energy electrons in dense target plasma generated by an ultra intense laser. Fast Ignition scenario (FIS) [1] requires for an intense electron beam to eventually propagate into dense plasma to heat fuel and to ignite fusion burning. The interaction between the high energy electron beam and dense plasma is important in FIS. Here we investigate dependence of the electron energy flux on the incident laser intensity in dense plasma region without density gradient by using 3D PIC simulations. Although the sharp density profile is not realistic, we believe that it may be still worth to investigate. We show that the interaction of high energy electrons with dense plasma induces electromagnetic instability, which causes the reduction of the high energy electron flux. We discuss effects of the relativistic thermal spread of the beam electrons on the electromagnetic instability.

2. 3D PIC Simulation

2.1. Simulation condition
We perform 3D PIC simulations with a box size of \( 24 \mu m \times 8 \mu m \times 8 \mu m \). Plasma is uniformly distributed within a region \( 2 \mu m \leq x \leq 22 \mu m \), with vacuum regions in both sides. Plasma density is 16 times greater than the laser critical density. Linearly polarized laser is irradiated in \( x \) direction from the left boundary with rising time of \( 3T_0 \), where \( T_0 = \lambda_0/c \) is laser oscillation period, and \( \lambda_0 \) is its wavelength. Polarization is in \( y \) direction. Normalized amplitude of the incident laser is varied as \( a = 3, 1 \) and \( 0.2 \). Here \( a = \frac{eE}{m_e\omega_0c} \), where \( E \) and \( \omega_0 \) are laser electric field intensity and its angular frequency, respectively, while \( e, m_e \) and \( c \) are electron charge, electron mass and speed of light, respectively. We
apply free boundary condition in x direction and periodic boundary condition in y and z direction.

2.2. Simulation results

Figure 1 shows spatial profiles of electron energy flux (EEF) for different laser intensity at time $t = 20T_0$ (left) and $t = 30T_0$ (right), where EEF is normalized by the incident laser flux $I_0 = c(4\pi)^{-1}E \times B$. In the case of $a = 3$, EEF is approximately $0.2I_0$ from $10\lambda_0$ to $15\lambda_0$ along x direction at time $t = 30T_0$, while in the case of $a = 1$, it is approximately $0.1I_0$ from $5\lambda_0$ to $15\lambda_0$ at the same time. In the case of $a = 0.2$, no visible flux appears. This result shows that the high energy electron flux can propagate into the high density plasma for the laser intensity about $a = 1$, and that the EEF increases remarkably with the increase of laser intensity above this laser intensity. It should be noted that the large reduction of the EEF near the surface for all cases is due to the filamentation instability as will be shown below. Hereafter we discuss the details for the case of $a = 3$.

Figure 1. Electron energy flux (EEF) normalized by incident laser intensity $I_0$ with different laser intensity, $a = 0.2$, 1 and 3 from bottom to top, at different times, $20T_0$ (left) and $30T_0$ (right).

Figure 2 shows spatial profiles of electron current in $x$-$y$ and $y$-$z$ planes at different times. The large reduction of the EEF near the plasma surface can be attributed to the current filamentation as observed in many previous works. The merging of the current filaments is also visible at time $t = 12.5T_0$. It should be noted that the results in Fig. 2 are obtained for the case of a super Gaussian laser profile in $y$-$z$ plane, but other results were obtained with uniform laser profile in $y$-$z$ plane.

Figure 2. Current profiles in $x$-$y$ plane at $t = 7.5T_0$ (top left), $10.5T_0$ (top right) and in $y$-$z$ plane at $x = 2.5\lambda_0$ at time $t = 7.5T_0$, $10.5T_0$ and $12.5T_0$ (bottom from left to right).

Figure 3. Normalized electron energy flux (EEF) at different time, from $12T_0$ to $24T_0$. The drift velocity of EEF front is about $0.8c$.

Figure 3 shows time evolution of EEF spatial profiles from time $t = 12T_0$ to $24T_0$ in detail. It shows that the front of the EEF propagates about $5\lambda_0$ within the duration of $6T_0$, from time $16T_0$ to time $22T_0$. This indicates that the propagation speed of the EEF front is about $0.8c$. This propagation velocity is
less than the velocity expected from the electron energy.

Figure 4 shows the spatial profiles of the EEF, the $x$ component electric field and the electron velocity distribution functions at three different positions in plasma at time $t = 18T_0$. The electric field is normalized by the incident laser electric field. This figure shows the increase of the $x$ component electric field near the front of the energy flux. The sharp decrease of the EEF may be therefore due to the scattering of the high energy electrons by the electric field caused by an electromagnetic instability. As shown in Fig. 4, the $x$ component of the high energy electron momentum has beam-like structure with the relativistic thermal spread near the front of the energy flux. It should be noted that the relation of $P_{x0} > P_{∥} > P_{⊥}$ is hold at least at $x = 11\lambda_0$, where $P_{x0}$ is the averaged $x$ component of the high energy electron momentum, and $P_{∥}$ and $P_{⊥}$ are the $x$ component and perpendicular component of their thermal spread, respectively. The thermal spread is also relativistic.

Figure 4. EEF (left top), $x$ component of electric field (left bottom) as function of $x$. Electron velocity distribution functions at the time $t = 18T_0$, parallel component (right top) and perpendicular component (right bottom).

3. Analysis of electromagnetic instabilities

Based on the simulation results shown above, we calculate the dispersion relation of the interaction between the high energy electron beam and dense background plasma, taking the relativistic thermal spread of the beam into account. Within our best knowledge, no one has considered the relativistic thermal spread of the beam to obtain the dispersion relation [2,3]. Namely in the previous study, the relativistic factor $\gamma = (1 + P_x^2/m_e c^2)^{1/2} = (1 + (P_{x0} + P_{∥})^2/m_e c^2 + P_{⊥}^2/m_e c^2)^{1/2}$, has been treated as a constant $\gamma_0 = (1 + P_{x0}^2/m_e c^2)^{1/2}$. As shown in Fig. 4, the $x$ component of the beam thermal spread can not be however neglected. We therefore expand the relativistic factor $\gamma$ to the first order of the thermal spread to investigate the growth rate of the electromagnetic instability.

Figure 5. Growth rate $\sigma = \text{Im}[\omega/\omega_{pe}]$ in $K_xK_y$ plane. The maximum value of the contour line is 0.145, decreasing at the rate of 0.02 each loop. The maximum growth rate of the dot in contour figure is about 0.155.

Figure 5 shows the normalized growth rate $\sigma = \text{Im}[\omega/\omega_{pe}]$ in wave vector $k$ space. Here $\omega_{pe}$ is background plasma frequency and $K_x$ and $K_y$ are the normalized wave number $K_x, y = k_x, y v_x, y/\omega_{pe}$. We have used the following parameters for the calculation of the growth rate, $\alpha = n_b/n_p = 0.05$, where $n_b$ and $n_p$ are beam and background plasma electron densities, $\rho_{∥} = n_{∥}/n_{b0} = 0.4$, $\rho_{⊥} = n_{⊥}/n_{b0} = 0.2$ and
\[ \rho_{p_{\parallel}, \perp} = v_{p_{\parallel}, \perp} / v_{\text{th}} = 0.05, \] where \( v_{b_{\parallel}, \perp} \) and \( v_{p_{\parallel}, \perp} \) are thermal velocity spreads of the beam and background plasma, respectively, and \( v_{\text{th}} \) is average beam drift velocity. There exist two instabilities, the Weibel instability and two-stream instability. The former corresponds to the branch with smaller \( K_x \ll 1 \) in \( k \) space, while the latter does to the branch with relatively large \( K_x \approx 1 \) in Fig. 5. It should be noted that if we use the constant \( \gamma_0 \), the two branches are separated with each other in \( k \) space for the parameters used. However when we take the relativistic thermal spread of the beam into the relativistic factor \( \gamma \), the two branches are connected in \( k \) space as shown in Fig. 5. And the electromagnetic mode corresponding to the Weibel instability continuously changes to the electrostatic mode corresponding to the two-stream instability with the increase of \( K_x \). The growth rate of the two-stream instability is much larger than that of the Weibel instability for the parameters used. It is known that the Weibel instability causes the current filamentation near the plasma surface as shown in Fig. 2. The Weibel instability occurs mostly in the perpendicular direction. As shown in Fig. 5, the maximum growth rate of the two-stream instability occurs for the perturbations propagating about 45 degree with respect to the \( x \)-axis for the parameters used.

Figure 6 shows a comparison of the maximum growth rate obtained in the first order expansion of the relativistic factor (solid line) with that using the constant relativistic factor \( \gamma_0 \) (dashed line) as functions of the beam drift velocity \( u_{\text{drift}} / c \), where \( u_{\text{drift}} = \gamma v_{\text{th}} \). The maximum growth rate corresponds to the two-stream instability. The maximum growth rate does not simply decrease with the increasing of \( u_{\text{drift}} / c \), when we take the relativistic thermal spread of the beam into the relativistic factor \( \gamma \). And it is always larger than that with using the constant relativistic factor. The difference between two growth rates becomes large for \( u_{\text{drift}} / c \approx 1 \) as shown in Fig. 6.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6}
\caption{Dependence of the maximum growth rate \( \sigma = \text{Im} \left( \omega / \omega_{\text{pe}} \right) \) on beam relativistic velocity \( u_{\text{drift}} \) with the first order \( \gamma \) (solid line) and the constant \( \gamma_0 \) (dashed line).}
\end{figure}

4. Conclusions and discussions
We have investigated the high energy electron transport in dense plasma with sharp density profile for different incident laser intensity with the use of 3D PIC simulations. We have observed the strong dependence of the electron energy fluxes on the laser intensity. We show that the high energy electron flux can propagate into the high density plasma only for the relatively laser intensity \( a \gtrsim 1 \), and that the EEF increases remarkably with the increase of laser intensity above the critical laser intensity. For the case of \( a = 3 \), we investigated space and time resolved velocity distribution functions in detail. The high energy electrons have a beam-like velocity distribution with relativistic thermal spread. We have discussed the electromagnetic instabilities associated with the high energy electron beam taking the relativistic thermal spread of the beam into account. Simulation results and the dispersion relation indicate that the electrostatic instability affects the high energy electron transport in dense plasma.

References
[1] Tabak M et al. 1994, Phys. Plasma 1 1626
[2] Bret A, Firpo M C and Deutsch C 2004, Phys. Rev. E 70 046401
[3] Bret A, Firpo M C and Deutsch C 2005, Phys. Rev. E 72 016403