High energy electron transport in dense plasma in fast ignition scenario

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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.

3D PIC SIMULATION

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 $a = eE/m_e\omega_0c$, 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.

Figure 1 shows spatial profiles of 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, 20 $T_0$ (left) and 30 $T_0$ (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), 10.5$T_0$ (top right) and in $y$-$z$ plane at $x = 2.5 \lambda_0$ at time $t = 7.5T_0$, 10.5$T_0$ and 12.5$T_0$ (bottom from left to right).
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 $5x_0$ 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 component (right top) and perpendicular component (right bottom). 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 $P_{x0}>P_{b}>P_{c}$ is hold at least at $x=11\lambda_0$, where $P_{x0}$ is the averaged $x$ component of the high energy electron momentum, and $P_{b}$ and $P_{c}$ are the $x$ component and perpendicular component of their thermal spread, respectively. The thermal spread is also relativistic.

**ANALYSIS OF INSTABILITY**

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 $\gamma=(1+P_{0}^2/m_{e}c^2)^{1/2}=(1+P_{b}^2/m_{e}c^2+P_{c}^2/m_{e}c^2)^{1/2}$, has been treated as a constant $\gamma_0=(1+P_{b0}^2/m_{e}c^2)^{1/2}$. 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 shows the normalized growth rate $\sigma=\text{Im}[(\omega+i\omega_{0})]$ in $K_{x}K_{y}$ 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.
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 $K_e$. 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 $u_{b0}/c$, where $u_{b0} = \gamma_0 v_{b0}$. The maximum growth rate corresponds to the two-stream instability. It should be noted that the growth rate becomes zero in the limit of $u_{b0}/c = 0$. The maximum growth rate does not simply decrease with the increasing of $u_{b0}/c$, 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 $u_{b0}/c \approx 1$ as shown in Fig. 6.

![Figure 6](image)  
**Fig.6.** Dependence of the maximum growth rate $\sigma = \text{Im}[\omega_{\omega b}]$ on beam relativistic velocity $u_{b0}$ with the first order $\gamma$ (solid line) and the constant $\gamma_0$ (dashed line).

Figure 7(a) shows the dependence of the maximum growth rates on the beam thermal spread, $\rho_{b10}$ and $\rho_{b10}$, for electrostatic and electromagnetic instabilities. Here, we fixed beam drift velocity at $u_{b0}/c = 1$. The maximum growth rate of the two-stream instability decreases as the parallel thermal spread increases. However, the decrease of the first-order RF solution is very small up to $\rho_{b10} < 0.4$, compared to that of the constant RF solution. The difference between the two solutions increases as $\rho_{b10}$ increases up to $\rho_{b10} < 0.6$. The maximum growth rate also decreases as $\rho_{b10}$ increases up to $\rho_{b10} < 0.4$. For the electromagnetic instability, the growth rate does not depend on the parallel spread, and there is also no difference between the two solutions. However, its growth rate decreases strongly as the perpendicular spread increases up to approximately $\rho_{b10} < 0.3$, and remains almost constant for large $\rho_{b10}$.

![Figure 7](image)  
**Fig.7.** (a) Dependence of maximum growth rate of electrostatic (solid line) and electromagnetic (dashed line) instabilities on beam thermal velocity spread; first-order RF solution (red), and constant RF solution (blue). Fixed parameters are $u_{b0}/c = 1$, $\rho_{b0} = 0.3$, $\rho_{b10} = 0.1$, and $\rho_{pl0} = 0.05$. (b) Dependence of wave number $|K|$ and propagation angle $\theta$ on perpendicular thermal spread; $\rho_{b10}$ varies from 0.05 to 0.4 from right to left with increments of 0.05. Fixed values of $\rho_{b0}$ are shown in figure. Here $K = kv_{b0}/\omega_{pe}$. 
We have also investigated the dependence of the wave number vector responsible for the maximum growth rate on the beam thermal spread. The normalized wave number $|k|$ varies from $|k| \approx 2.5$ to 1 and the propagation angle $\theta$ varies from $\approx 70$ to 0 degrees as $v_{b,\perp}$ increases from 0.05 to 0.4, as shown in Fig. 5(b). The perpendicular spread strongly affects the propagation direction of the instability. However, we observed that the parallel spread does not greatly affect either $|k|$ or $\theta$.

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 $a \geq 1$, 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


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