Distortion of Bulk-Electron Distribution Function and Its Effect on Core Heating in Fast Ignition Plasmas

Hideaki MATSUURA, Yasuyuki NAKAO and Tomoyuki JOHZAKI[1)]

Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Motooka 744, Fukuoka 819-0395, Japan

[1)]*Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan*

(Received 6 December 2009 / Accepted 15 June 2010)

A possibility of distortion in bulk-electron velocity distribution function due to injection of intense laser-induced (LI) fast electrons is examined. The Fokker-Planck (FP) equations for LI-fast and bulk electrons are simultaneously solved consistently considering the time evolution of Rosenbluth potentials in two-dimensional (2D) velocity space. The FP simulation shows that an asymmetric distortion of bulk-electron distribution function becomes appreciable when number density of the fast electrons relative to bulk plasma is increased, and that when bulk electrons are assumed to be Maxwellian, the propagation distance of LI-fast electron tends to be shorter due to overestimated power deposition compared with the case when distortion process of the bulk electron distribution is considered.

Keywords: distortion of bulk-electron velocity distribution function, laser-induced fast electron, Fokker-Planck equation, fast ignition plasma

DOI: 10.1585/pfr.5.S2070

1. Introduction

To realize the energy production in a fast ignition scheme, complete clarification of the energy-transfer process from laser-induced (LI) fast electrons to dense core plasma is required. A part of the energies carried by fast electrons may be transferred to core plasma via electromagnetic forces induced by energetic electrons. In a dense plasma, however, collisional interaction is dominant for energy-transfer process from fast electrons to bulk plasma, and a slowing-down (≤ 100 keV) component in LI electrons particularly contributes to the local plasma heating. The shape of the velocity distribution functions of both slowing-down and bulk electrons would determine an important physics of the heating process.

So far, energy distribution function for fast electrons has been investigated using sophisticated simulation codes [1]. In most of the previous studies, however, the interaction between fast electrons and bulk plasma (power deposition from fast electrons to bulk plasma) has been estimated without considering the distortion of the bulk-electron distribution function. The bulk electrons which have relative velocity close to the fast electrons would interact more frequently via Coulomb force than much slower ones. If we look at the problem in considerable short time scale, i.e. less than femto-second order, distribution function of bulk electrons may once change its shape from Maxwellian and gradually relaxes toward Maxwellian with higher temperature than before. The assumption that electrons keep Maxwellian during the energy transfer process implies that the deflection time of bulk-electron distribution function is neglected (the bulk electron distribution function is considered to be instantaneously isotropized and relaxed to Maxwellian).

In this paper, we focus our attention on the Coulombic collisional interaction as a possible drive force for the distortion of bulk electrons. By solving Fokker-Planck equation for both LI-fast and bulk electrons simultaneously considering the time evolution of Rosenbluth potentials in two-dimensional (2D) velocity space, we examine whether a distortion of the bulk-electron distribution function from Maxwellian due to collisions with LI-fast electrons can be appreciable or not. By comparing the present calculation with the one in which the deflection time is neglected (bulk electrons are assumed to keep Maxwellian during the heating process), we examine whether the distortion can be influential on the bulk plasma heating process or not.

2. Analysis Model

An intense electron-beam injection in Maxwellian plasma is considered. The LI-fast and bulk electron distribution functions $f_a(v_{//}, v_\perp)$ are obtained by simultaneously solving the following Fokker-Planck (FP) equations;

$$\frac{\partial f_a}{\partial \tau} + u_{//}\frac{\partial f_a}{\partial \xi}$$
$$= -\frac{\partial}{\partial u_{//}}\left(\frac{\partial H}{\partial u_{//}} f_a\right) - \frac{1}{u_\perp}\frac{\partial}{\partial u_\perp}\left(u_\perp \frac{\partial H}{\partial u_\perp} f_a\right)$$
$$+\frac{\partial}{\partial u_{//}}\left[\frac{\partial^2 G}{\partial u_{//}^2}\frac{\partial f_a}{\partial u_{//}} + \frac{\partial^2 G}{\partial u_{//}\partial u_\perp}\frac{\partial f_a}{\partial u_\perp}\right]$$

author's e-mail: mat@nucl.kyushu-u.ac.jp

$$+\frac{1}{u_\perp}\frac{\partial}{\partial u_\perp}\left[v_\perp\left(\frac{\partial^2 G}{\partial u_{//}\partial u_\perp}\frac{\partial f_a}{\partial u_{//}}+\frac{\partial^2 G}{\partial u_\perp^2}\frac{\partial f_a}{\partial u_\perp}\right)\right]. \qquad (1)$$

The subscript a represents LI-fast or bulk electron. The right-hand side of Eq. (1) is the 2D FP collision term. The Rosenbluth potentials H and G are obtained using the LI-fast and bulk electron distribution functions at each time steps;

$$H=\sum_b\left(\frac{Z_b}{Z_a}\right)^2\left(\frac{m_a}{m_b}\right)\int\frac{f_b(\vec{u}')}{\left|\vec{u}-\vec{u}'\right|}\mathrm{d}\vec{u}', \qquad (2)$$

$$G=\frac{1}{2}\sum_b\int\left|\vec{u}-\vec{u}'\right|f_b(\vec{u}')\mathrm{d}\vec{u}', \qquad (3)$$

where subscript b represents the ion, LI-fast or bulk electron (the collision between LI-fast electrons is neglected). Here $u_{//}$ and $u_\perp$ denote parallel and vertical velocity components relative to the electron-injected (x-axis) direction. The variables are normalized so that $u = v/v_0$, $\xi \equiv x/\tau_0 v_0$ and $\tau \equiv t/\tau_0$, where $v_0 = \sqrt{2T_0/m_\mathrm{e}}$, $\tau_0 = 4\pi\varepsilon_0^2 m_\mathrm{e} v_0^4/e^4 \ln\Lambda$. During the calculations the normalized parameter T_0 is set to 2 keV. The bulk ion distribution function is assumed to be kept in Maxwellian. To examine the response of ion temperature to deposited power, the following expression is introduced.

$$\frac{\mathrm{d}(3/2nT)}{\mathrm{d}t}=P_{\mathrm{LI}\to\mathrm{i}}+P_{\mathrm{bulk}\to\mathrm{i}}. \qquad (4)$$

In this paper since we look at the phenomena in only local (narrow) area in short time duration, the energy sink and spatial derivative terms are ignored. Here the transferred power $P_{a\to b}$ from species a to b is evaluated using the distribution functions f_a and f_b as

$$p_{a\to b}=-\int\frac{1}{2}m_\mathrm{e}v^2\left(\frac{\partial f_a}{\partial t}\right)_b \mathrm{d}\vec{v}. \qquad (5)$$

The second term in the left-hand side of Eq. (1) represents the streaming of electrons along x-axis (beam axis).

To look at the distortion of bulk electron distribution function, we consider an intense electron-beam injection into an uniform 1 keV deuterium-tritium (DT) Maxwellian plasma. As for the beam injection, the LI-fast-electron distribution function at $x = 0$ is fixed as

$$f_\mathrm{LI}=c\exp\left(-\frac{m_\mathrm{e}}{2T_{//}}(v_{//}-v_\mathrm{peak})^2-\frac{m_\mathrm{e}}{2T_\perp}v_\perp^2\right), \qquad (6)$$

during the calculation. This treatment is equivalent to assuming the stable electron source at $x = 0$. At the other side of the boundary, the electrons freely escape from the calculation space. The coefficient c is obtained from the fast-electron density, and the broadness of the fast-electron distribution function can be determined by parameter $T_{//}$ ($u_{//}$ direction) and $T_\perp$ ($u_\perp$ direction). Throughout the calculations $T_{//}$ and $T_\perp$ are fixed at 10 keV and 1 keV respectively. In this paper we choose the v_peak as electron velocity corresponding to 100 keV energy.

Generally LI-fast electrons in the typical fast ignition plasma have much higher energies. As a result of the relativistic effect, however, the relative velocity between ~MeV and 1 keV electron is not significantly different from the one between 100 keV and 1 keV electron. Furthermore because the Rutherford cross section is inversely proportional to fourth powers of the relative velocity, much lower (~ keV) electrons have more important roles for the distortion of bulk-electron distribution. As a first step, we estimate the presence of the bulk-electron distortion without considering a contribution of the relativistically energetic electrons.

3. Results and Discussion

In Figure 1 we first show the time evolution of spatial profiles of (a) ion temperature, (b) LI-electron density and (c) transferred power from LI-fast electrons to ions $P_{\mathrm{LI}\to\mathrm{i}}$. In this case, bulk ion and electron densities are taken as $n_\mathrm{i} = n_\mathrm{e} = 10^{31}\,\mathrm{m}^{-3}$ and LI-fast-electron density $6\times10^{27}\,\mathrm{m}^{-3}$ are assumed (the LI-fast-electron intensity I_LI is roughly estimated as $\sim 2\times10^{18}\,\mathrm{Wcm}^{-2}$). The LI-fast electrons percolate into the target plasma and ion temperature gradually increases owing to the collisional power deposition from fast electrons.

To look at the effect of the distortion of the bulk electron distribution function, we also carried out a similar simulation assuming a Maxwellian for bulk-electron distribution function. The result is presented in Fig. 2. The calculation conditions are the same as those in Fig. 1. From the comparison between Fig. 1 and Fig. 2, it is found that when FP equation for bulk electrons is solved, the LI-fast electrons infiltrate into the plasma more quickly. The peak temperature when Maxwellian is assumed for bulk electrons is somewhat higher than that when FP equation is solved.

In Figure 3 the transferred energy from LI-fast electrons to bulk ions $E_{\mathrm{LI}\to\mathrm{i}}$ and electrons $E_{\mathrm{LI}\to\mathrm{e}}$ are compared between when FP equation for bulk electrons is solved (Fig. 1) and Maxwellian is assumed (Fig. 2). The transferred power is obtained by integrating $P_{\mathrm{LI}\to\mathrm{i}}$ ($P_{\mathrm{LI}\to\mathrm{e}}$) with respect to x and time t' as

$$E_{a\to b}(t)=\int_0^t\int_0^{5\mu\mathrm{m}}P_{a\to b}(x,t')\mathrm{d}x\mathrm{d}t'. \qquad (7)$$

The solid lines represent the transferred energy from LI-fast electrons to bulk ions, and the dotted lines denote the energy from LI-fast to bulk electrons. In Fig. 3 provided energy by LI-fast electrons is also presented in the bold line. We can see that the transferred energy from LI-fast electrons to bulk ions is not different so much between the two cases. On the other hand the difference in the transferred energy from LI-fast electrons to bulk electrons is clearly recognized. When Maxwellian is assumed, the LI-fast electrons deposit relatively larger power to bulk electrons per unit time and slow down relatively faster

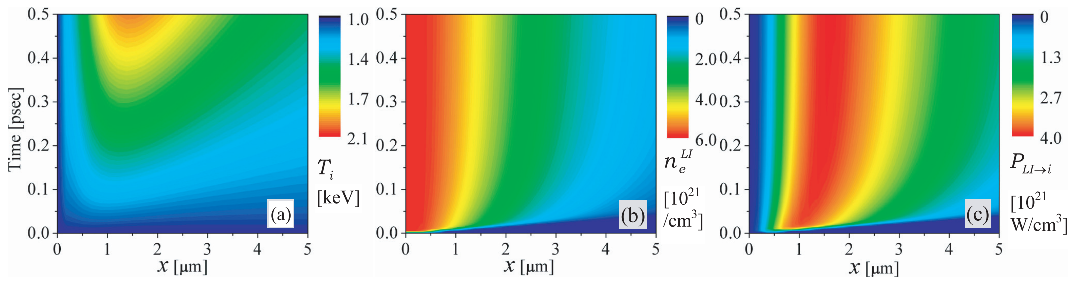

Fig. 1 Time evolution of spatial profiles of (a) ion temperature, (b) LI-fast electron density and (c) deposited power from LI-fast electron to ion P_{LI-1} when FP equations for LI-fast and bulk electrons are solved.

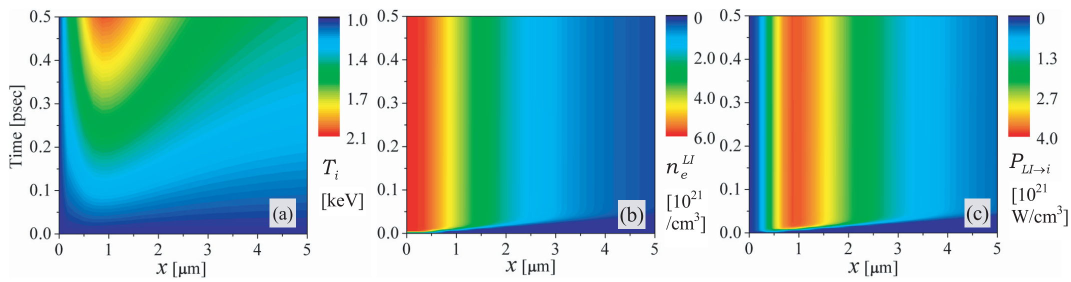

Fig. 2 Time evolution of spatial profiles of (a) ion temperature, (b) LI-fast electron density and (c) deposited power from LI-fast electron to ion P_{LI-i} when FP equation for LI-fast electron is solved and bulk electrons are assumed to be Maxwellian.

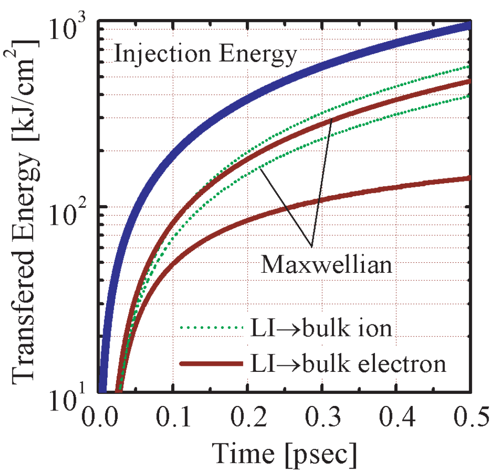

Fig. 3 Transferred energy (derived by integrating transferred power with respect to t and x) from LI-fast electron to bulk ion and electron. The bold line represents total injection energy.

compared with the case when FP equation is solved (see Fig. 1 and 2). Because the transferred energy from LI to bulk electrons decreases, the LI-fast electrons more rapidly reach the boundary and are lost from the calculation space. So the transfer energy from LI to bulk electrons decreases with only the quantity of the increased loss energy.

To clarify the reason why the difference in the transferred power from LI-fast electron to bulk electron (in Fig. 3) appears, we next look at the bulk electron velocity distribution function. The distortion of bulk electron distribution was evaluated by comparing the obtained distribution function with Maxwellian having effective temperature of distorted distribution function. The effective temperature of the bulk-electron distribution function was estimated by comparing the thermal component of the obtained bulk-electron distribution function with a Maxwellian by mean of the least squares fitting [2]. The deviation of bulk-electron distribution from Maxwellian,

$$\Delta f_{\mathrm{bulk}} = f_{\mathrm{bulk}} - f_{\mathrm{bulk}}^{\mathrm{Maxwellian}}, \tag{8}$$

is exhibited in Fig. 4 for $t = 0.1$ psec at $x = 1.5\,\mu$m. It is found that the bulk-electron distribution function is deviated from Maxwellian especially in the velocity region of $\sqrt{u_{//}^2 + u_{\perp}^2} \leq 2$. Since the Rutherford cross section is inversely proportional to the fourth powers of relative velocity, the energetic bulk electrons more frequently interact with LI-fast electrons and receive much energy as a whole. As a result of the pitch-angle scattering of those heated electrons, the energetic component in the bulk electron distribution function increases in both directions. In this case, the magnitude of the deviation from Maxwellian is $\Delta f_{\mathrm{bulk}}/f_{\mathrm{bulk}} \approx 10^{-3} \sim 10^{-2}$. As a result of the deviation from the Maxwellian, the averaged relative speed between LI-fast and bulk electrons increases and the transferred energy from LI to bulk electrons decreases. The deviation would gradually calm down with increasing temperature and bulk-electron distribution function would eventually relax toward Maxwellian.

When the bulk electron distribution function is assumed to be Maxwellian, i.e bulk electron distribution

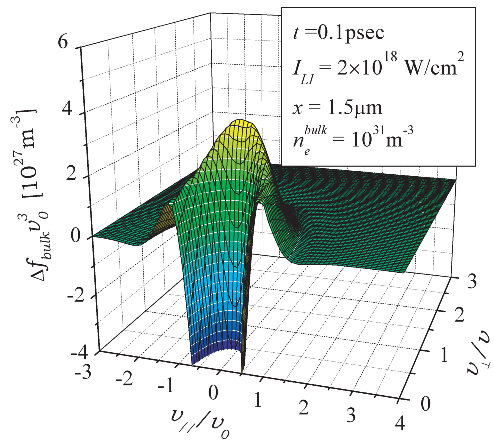

Fig. 4 Deviation of bulk-electron distribution function from Maxwellian, $\Delta f_{\text{bulk}} \equiv f_{\text{bulk}} - f_{\text{bulk}}^{\text{Maxwellian}}$. Beam injection power $I_{\text{LI}} = 2 \times 10^{18}$ W/cm^2 is assumed.

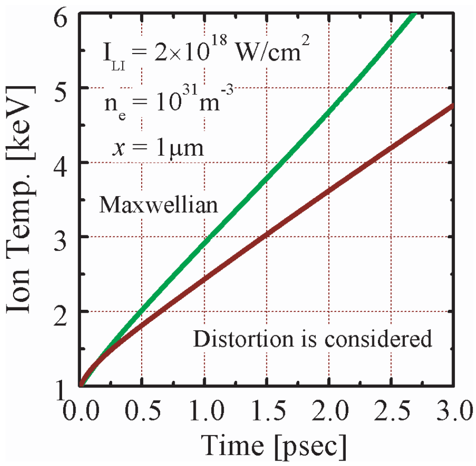

Fig. 5 Time evolution of ion temperature when 2×10^{18} W/cm^2 of LI-fast electrons are injected.

function is assumed to be instantaneously isotropized and relaxed to Maxwellian, the transferred energy from LI-fast to bulk electrons per unit time tends to be overestimated compared with the case when we consider the distortion. In such a case the LI-fast electrons lose their energy more quickly in narrower region, and spatial propagation distance tends to be shorter compared with the case when we consider the distortion. It should be noted that if slowing down of LI-fast electrons is accelerated, the interaction between LI-fast electrons and bulk ions (electrons) is further intensified. Although the deviation of the bulk-electron distribution function from Maxwellian with the same effective temperature is small, as a result of repetition of these processes, the difference in the transferred energy from LI-fast to bulk electrons gradually increases as simulation is progressed (see Fig. 3).

Finally we quantitatively evaluate the effect of the distortion. The time evolution of the ion temperature at $x = 1\,\mu$m is shown in Fig. 5. The calculation condition is the same as the one in Fig. 1 and Fig. 2. When Maxwellian is assumed for bulk electrons, the ion temperature reaches 4 keV in ~1.6 psec, which is roughly 30% faster than the case when distortion is considered, i.e. ~2.3 psec. Contrary to this, with distance from the injection region, ion temperature becomes higher for the case when the distortion is considered since the spatial propagation is faster (e.g., at $x = 2\,\mu$m, the temperature is higher for the distortion included case).

In actual fast ignition plasmas, fast electrons may be generated with much broadened (higher) energy spectrum. Throughout the calculations, $T_{//}$ has been taken as 10 keV. If a fraction of low-energy component in LI-fast-electron distribution function increases, the collisional interaction between LI-fast electrons and bulk plasma would be further intensified. In such a case the effect of the distortion of bulk electron distribution function on plasma heating may be more conspicuous. In this paper a contribution of the relativistically energetic electrons has been neglected. As far as we consider the problem only in the local (narrow) area in a fast ignition plasma, the energetic component would not be influential so much on the present results. Throughout the calculation, time variation of the bulk-ion spatial profile has not been taken into account. The energy sink tem was ignored in Eq. (4). To carry out more accurate evaluation, spatial diffusion (power-loss mechanism) for bulk ions should be included, and this is our next work. When electron beam passes through much lower density region, the distortion may be affected strongly by the electric field [3]. In such a case accurate treatment for electric field, e.g. coupling with the Poisson equation, should be incorporated into the analysis.

Throughout the simulations, it is found that the distortion of the bulk-electron distribution function due to interaction with laser-produced fast electrons certainly occurs and as far as we look at the phenomena in the local (narrow) area, the distortion noticeably affects the temporal behaviors of the ion temperature. To examine the overall effect of the distortion on the burn process, further large-scale integrated simulation would be necessary.

[1] See, for example, Y. Sentoku *et al.*, Phys. Plasmas **11**, 3083 (2004); T. Yokota *et al.*, Phys. Plasmas **13**, 022702 (2006).
[2] H. Matsuura *et al.*, Phys. Plasmas **14**, 054504 (2007).
[3] A. J. Kemp *et al.*, Phys. Rev. Lett. **97**, 235001 (2006).