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Hot electron emission limited by self-excited fields from targets irradiated by ultra-intense laser pulses

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Abstract. A large number of hot electrons exceeding the Alfvén current can be produced when an ultra-intense laser pulse irradiates a solid target. Self-excited electrostatic and magnetic fields at the target rear could influence the hot electron transport. To investigate the influence, we measure the hot electrons when a pre-plasma is created on the target rear surface and verify an increase of the electron number by a factor of 2 comparing to the no rear plasma case. The increase may be caused because of changes in the electrostatic potential formation process. The retardation of the potential formation is shown using a particle-in-cell simulation. The electron number escaping within the retardation time duration is consistent with our estimation taking the Alfvén current into account.

1. Introduction

In the interactions of ultraintense laser and plasma, hot electrons can be produced with the conversion efficiency of few tens percents [1]. The hot electrons are prospected to be an energy carrier to heat the imploded plasma core in the fast ignition scheme [2]. The hot electron characteristics have been studied such as energy spectra, angular distributions, and conversion efficiencies.

According to measurements of hot electrons produced by a high energy laser pulse, it is well known that the measured electron number in vacuum is quite small comparing to the conversion efficiency observed by the K_α X-ray measurements. Sheath fields have been contemplated as a candidate to cause the discrepancy. The influence of the sheath field, however, has not been evaluated on the electron transport. Other candidate of the discrepancy is the self-excited magnetic field. The magnetic field may be strong enough to limit the electron current as known as the Alfvén limit.

In this study, the influence of the sheath and magnetic fields is investigated on the electron transport at the target rear surface. In the experiments, a pre-plasma is generated on the target rear surface (rear plasma), which can weaken the electrostatic field. The number increase of hot electrons is found with the rear plasma in our experiments. It is shown that the rear plasma retards the potential evolution using one-dimensional particle-in-cell (PIC) simulations. Hot electrons can be emitted for longer time when the potential evolution is retarded because the hot electrons can overcome the sheath potential wall only

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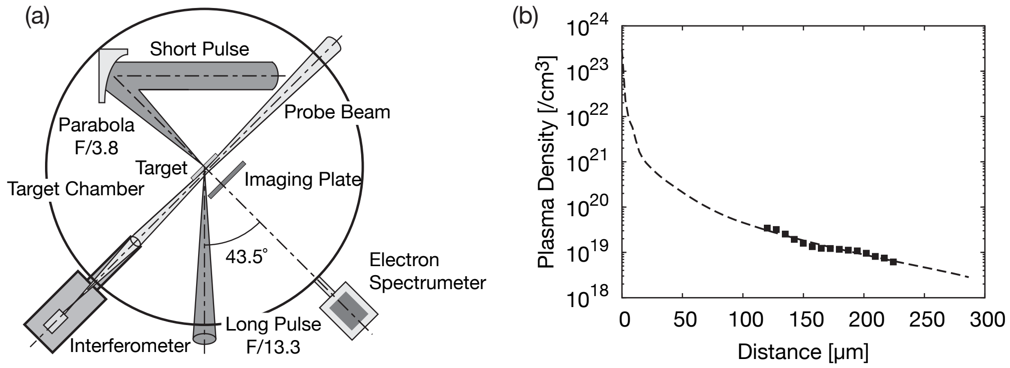

Figure 1. (a) Experimental setup. (b) Typical density profile of the rear plasma measured with the interferometer (points). Dashed curve is a simulation result.

when the potential is lower than their kinetic energy. The emitted number of hot electrons within the retarded time duration is also discussed using the Alfvén current. In our arguments, the hot electron number per time, i.e. the electron current, shows a good agreement with the Alfvén current within the duration.

2. Experimental Setup and Results

An ultraintense laser pulse (λ = 1.053 μm) irradiates a plane target with energies of 1–10 J. The laser pulse duration and the focused spot size are 700 fs and 20 μm, respectively. The target is a 50-μm-thick aluminum foil. The laser pulse generates hot electrons with energies up to 30 MeV in the forward direction by the Ponderomotive force because of the *s*-polarized irradiation. The emitted hot electrons are measured around the laser propagating direction with imaging plates (IPs) as shown in the Fig. 1 (a). An energy spectrometer of electrons is attached on the laser axis. The spectrometer can measure the absolute number of hot electrons because the IP used in the spectrometer has been calibrated as an electron detector [3]. Angular distributions of electrons are also measured at around the axis. The total number of emitted hot electrons is estimated from both of the energy spectrum and the angular distribution, which are measured simultaneously.

A temperature of hot electrons T_e is estimated from the approximation of the energy spectrum with the relativistic Maxwellian, $n(\varepsilon) \propto (\varepsilon/T_e)^2 \exp(-\varepsilon/T_e)$. In the case of without rear plasma, the temperature depends on the laser intensity as shown in the Fig. 2 (a) (solid circles). Scalings given by Refs. [4, 5] are also shown. The relations of the number and the temperature of electrons are shown in the Fig. 2 (b) (solid circles). In the experiments, the laser intensity is varied by controlling the energies of the short pulse. The electron number is increased with the higher laser intensities, namely, the higher laser energy.

A rear pre-plasma is created by a long pulse laser light (λ = 1.053 μm). The long pulse with a 400 ps duration irradiates the rear surface of the foil with the intensity of 10^{13} W/cm^2. The time delay between the long pulse to the short pulse is 400 ps. The density profile of the rear plasma shown in the Fig. 1 (b) is measured with an interferometer using a probe beam (λ = 0.527 μm) at the timing of short pulse irradiation. In the figure, the dashed curve is obtained with 1D hydrodynamic simulations. The scale length of the rear plasma is typically 60 μm at around the density of 10^{19} cm^{-3}.

When the laser intensity of short pulse is similar, the electron temperature measured by the spectrometer is not so changed with the rear plasma existence as shown in the Fig. 2 (a) (open circles). The electron number is shown in the Fig. 2 (b) (open circles) for the rear plasma case. When the rear plasma exists, the electron number increases comparing the numbers between two cases at the similar temperature. The factor of the number increase is about 2. The signal level on IP is negligible when only the long pulse irradiates the target.

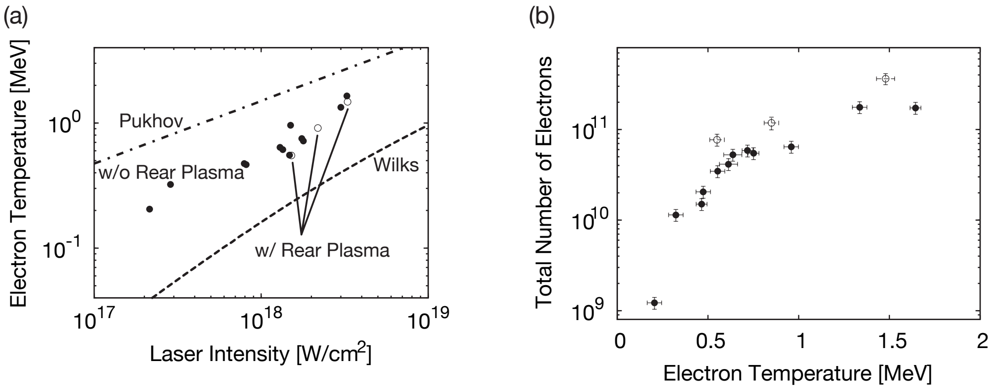

Figure 2. (a) Laser intensity dependence of electron temperatures measured. (b) Electron temperature vs. measured electron number. The solid circles (•) and the open circles (∘) are obtained without the rear plasma and with the rear plasma, respectively.

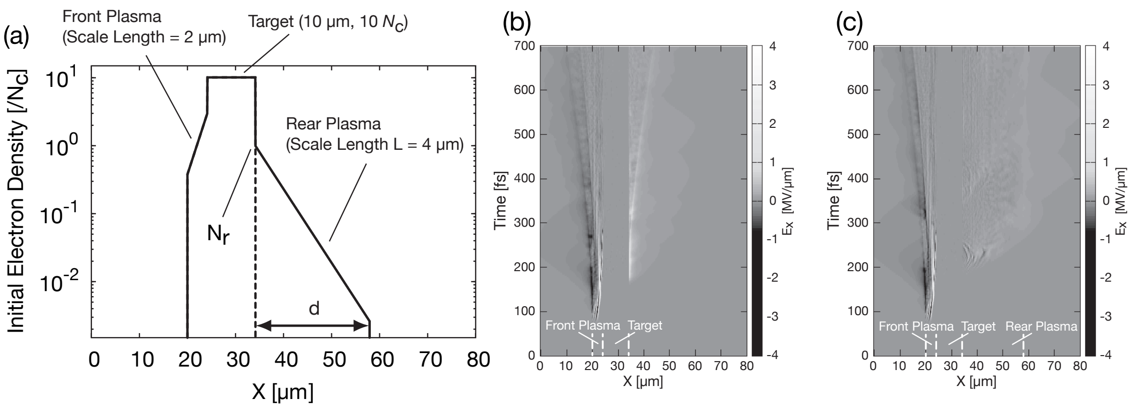

Figure 3. (a) The plasma density profile in the simulation ($L = 4$ μm). The temporal profile of the sheath field is shown (b) without the rear plasma case and (c) in the rear plasma case.

3. PIC Simulations and Discussion

1D PIC simulations are performed to investigate the influence of the rear plasma. The plasma conditions are shown in the Fig. 3 (a). In one case (dashed line), the target (with density of $10N_c$, N_c is the critical density for 1 μm lasers) has a sharp boundary at the backside. In another case (solid line), the target has a rear plasma. An ultraintense laser pulse (1 μm) irradiates the target with an intensity of 5.5×10^{18} W/cm^2. In this study, the pulse duration of ultraintense laser T and the scale length of rear plasma L are varied to investigate the temporal evolution of sheath field or potential. The relations between the pulse duration and the plasma profile are kept in constant as $cT/L = 35 \sim 45 \times 10^{-9}$. Here, c is the speed of light. The thickness of rear plasma d is also varied to keep a certain density at the edge of rear plasma. The Fig. 3 (b) and Fig. 3 (c) show the temporal profile of the sheath field in the case of without rear plasma and with rear plasma, respectively. Here, the parameters are $(T, L) = (60$ fs$, 4$ μm$)$. It is found that the sheath fields are weakened when the rear plasma exists.

The sheath potential is an important parameter for the hot electron emission because the electrons are required to have higher kinetic energies than the potential. The temporal evolution of the potential is shown in the Fig. 4 (a). Here, the potential is estimated for an electron (with a velocity of c) departing from the target rear boundary at a certain time. The solid (dashed) curve is obtained in the with (without)

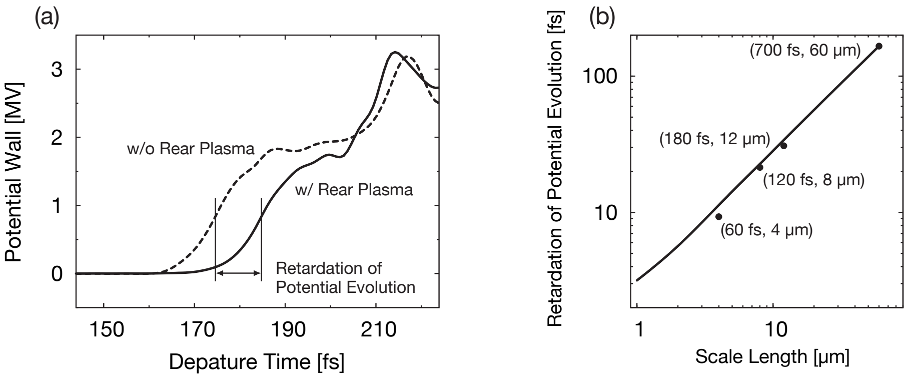

Figure 4. (a) The temporal profile of the sheath potential at the target backside. (b) The retardation duration in PIC simulations (points). The solid line is estimated from our arguments.

rear plasma for $(T, L) = (60\ \text{fs}, 4\ \mu\text{m})$. There is a retardation of the potential evolution with the rear plasma. The potential retardation enables the hot electrons to escape from the target for a longer time, and could cause the number increase of the emitted electrons. The Fig. 4 (b) shows the potential retardation for several conditions. The potential retardation increases with longer pulses and larger rear plasmas. The potential retardation is 100–150 fs for the experimental condition, $(T, L) = (700\ \text{fs}, 60\ \mu\text{m})$.

The potential retardation is evaluated using a simple model. The potential retardation is caused because the return currents can compensate the charge separation within the rear plasma. The electron number for the return current in the rear plasma is LN_r at the maximum when the density profile of rear plasma is $N(x) = N_\mathrm{r} \exp(-x/L)$. Here, the electron current is treated in 1D. The hot electron number per time is given as cN_h. Here, the hot electron density is N_h, which is assumed to be N_c. We introduce the time duration τ that the return current can be supplied at the maximum. The duration is then given as $\tau = LN_\mathrm{r}/(cN_\mathrm{c})$ when the velocity of hot electrons is assumed to be c. The estimated duration τ agrees with the potential retardation as shown in the Fig. 4 (b) (solid curve). It should be noticed that the pulse duration of the ultraintense laser T is much longer than the retarded duration τ in our simulations.

The influence of the self-excited magnetic fields should be also taken into account to investigate the electron emission from the target even within the retardation duration of potential evolution. Here, we introduce the Alfvén current. The electron number is $0.5 \sim 1.0 \times 10^{11}$ contained within the Alfvén current with 100–150 fs duration, which is the retarded duration time in the experimental condition. This number agrees well with the number increase measured in the experiments as shown in the Fig. 2 (b).

4. Summary

The number increase of hot electrons is found in the experiments when the pre-plasma exists on the rear surface of foil targets. The influence of the rear plasma is investigated using 1D PIC simulations. The sheath field is weakened and the sheath potential evolution is retarded by the rear plasma. The number increase of hot electrons shows a good agreement with the electron number which can propagate within the retarded time duration limited by influence of the self-generated magnetic field.

References

[1] K. Yasuike *et. al. Rev. Sci. Instrum.*, **72**, 1236 (2001).
[2] M. Tabak *et. al. Phys. Plasmas*, **1**, 1626 (1994).
[3] K. A. Tanaka *et. al. Rev. Sci. Instrum.*, **76**, 013507 (2005).
[4] S. C. Wilks *et. al. Phys. Rev. Lett.*, **69**, 1383 (1992).
[5] A. Pukhov *et. al. Phys. Plasmas.*, **6**, 2847 (1999).