Multi-Stage Ionization Dynamics of Carbon Film Irradiated by High Power Lasers

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By using a particle code including ionization and atomic processes, we investigated the ionization dynamics of carbon film irradiated by an intense laser pulse. We found two types of ionization dynamics, namely, a fast time scale convective propagation of the ionization front with C^{4+} triggered by induced plasma waves, and a slow front with C^{5+} and C^{6+} triggered by heated electrons due to non-local thermal conduction. Thus, ionization dynamics in solids were found to evolve through multiple stages.

Keywords:

high power laser-matter interaction, ionization dynamics, plasma waves, non-local transport

The development of high-intensity short-pulse lasers opens up various applications based on laser-matter interaction, such as laser fusion, compact particle accelerators, high intensity short pulse X-ray and neutron sources, etc. [1]. Many computational works using the particle-in-cell model have been done; however, most of them made an priori assumption of an ideal plasma as an initial condition. For applications utilizing relatively high-Z materials, atomic and relaxation processes play an important role in determining the interaction. In order to study such applications, we have developed a particle based integrated code (EPIC3D) which includes various atomic and relaxation processes [2]. By using the code, we investigated the ionization dynamics in carbon film irradiated by a short-pulse high-power laser, which had not been clarified previously.

Here, we carry out two-dimensional simulations in a box of size L_x = 13.12 μm by L_y = 1.64 μm, where carbon film is set in 2.56 μm < x < 10.76 μm. A p-polarized laser is emitted in the x-direction from the antenna placed at x = 0. Here, we employ a transparent boundary condition in the x-direction, and a periodic one in the y-direction. The laser parameters consist of a wavelength of λ = 0.82 μm, a pulse width of 100 fs, and a peak intensity of 5.1×10^{19} W/cm^2. As for the atomic process, we consider a tunneling field ionization and an ionization by electron impact, where the cross sections are given by the ADK [3] and the BEB formula [4]. The relaxation process is modeled by the Monte-Carlo method via successive binary collisions of particle pairs.

The time histories of the mean electron and ion energies as well as the field energy are shown in Fig. 1(a) and those of ion abundance for each charge state C^{q+} are shown in Fig. 1(b). After the laser pulse hits the film, ionizations are successively triggered from C^{1+} to higher charge state. The charge state q = 4 is triggered at around t = 30 fs, and the number of C^{4+} significantly increases, showing a clear linear dependence with time. On the other hand, the number of C^{5+} and C^{6+} ions also increases linearly with time, but the rate of increase is small compared with that for C^{4+} (roughly 1/8). Furthermore, the number of C^{5+} and C^{6+} ions gradually increases even after the direct interaction with the laser pulse has ceased.

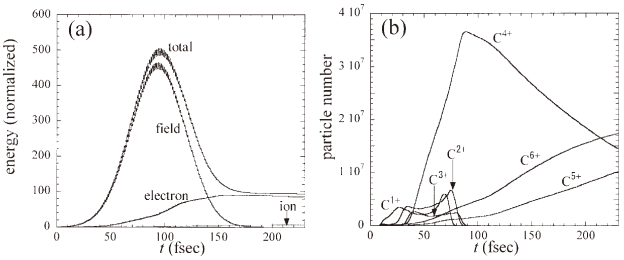

Fig. 1 (a) Time histories of electron, ion, and field energies and (b) time histories of ion abundance for each charge state q.

Figure 2 shows the normalized ion charge density profiles ($\Sigma_j q_j n_j / e n_0$) at different time scales, i.e., panel (a) shows profiles from 30.8 fs to 82.1 fs and panel (b) shows those from 82.1 fs to 225.1 fs. Here, n_j and q_j(= je) represent the ion density and charge of the charge state j, and n_0 is the solid carbon density. From the localized high density region near the surface, ionization proceeds inside, and a density hump with a steep density gradient in the front is formed. Note that a dip structure is revealed between the surface and the

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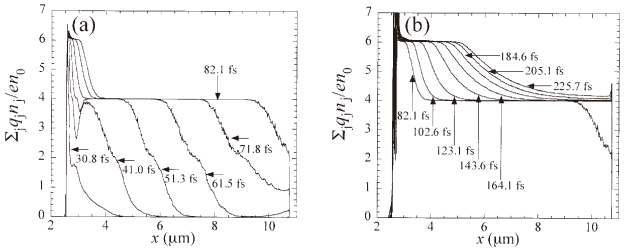

Fig. 2 Ion charge density distributions from 30.8 fs to 82.1 fs (a) and from 82.1 fs to 205.1 fs (b).

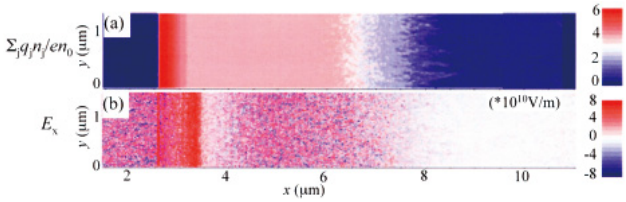

Fig. 3 (a) Ion charge density, (b) longitudinal electric field (E_x) at t = 61.5 fs.

hump (x ~ 1 μm). Then, the front convectively propagates deep inside and reaches the rear side (t = 82.1 fs), leading to a flat density structure over the whole carbon film. The density in the flat region corresponds to the density at which the carbon is thoroughly ionized to C^{4+}. Hence, it is concluded that the propagation observed in Fig. 2(a) corresponds to an ionization front to the charge state q = 4. The speed of the front is estimated as 1.3×10^8 m/s. Followed by the propagation of C^{4+}, ionizations to higher charge states, i.e. q = 5 and q = 6, are triggered and the front also starts to convectively propagate from the surface region to the inside. However, the front speed is around 1.7×10^7 m/s, which is one order magnitude slower than that for C^{4+}, suggesting that the ionization mechanism is different. Furthermore, even after the passage of the laser pulse, the ionization keeps proceeding, but its propagation characteristics change from "convective" to "diffusive" as seen in the downstream region on the rear side.

We next investigated the ionization process for each electronic state of carbon ions. As a result, we found that the ionizations up to q = 4 were mainly due to field ionization, whereas those to q = 5 and q = 6 were due to electron impacts. Therefore, it is concluded that the fast convective propagation results from field ionization, whereas the subsequent slow one results from ionization due to electron impact.

Figure 3 shows the spatial distributions of (a) the ion charge density (ρ_i) and (b) the longitudinal electric field (E_x) at 61.5 fs. In Fig. 3 (a), the complex corrugated structures of charge density are observed in 3.5 μm < x < 5.5 μm, which corresponds to the ionization front with a steep density gradient. As also seen in Fig. 3(b), micro-scale electric fields that are oscillating similar to those in turbulence are excited from the front region toward the upstream direction. The amplitude of the waves is of the order of 10^9 V/cm, which is close to the threshold value of ionizations from C^{2+} to C^{3+} and, subsequently, C^{4+}. We also investigated the characteristic of the waves and found that the relation $\omega_p \sim k_x v_e$ is approximately satisfied, where $k_x \sim 9 \times 10^5$ cm^{-1} is the typical wave number, $\omega_p \sim 2.7 \times 10^{16}$ s^{-1} is the plasma frequency for C^{2+} plasma, and $v_e \sim 3 \times 10^{10}$ cm/s is the typical velocity of fast electrons produced near the surface. This suggests that the Cherenkov emission of plasma waves may be the origin of the field ionization [5].

Furthermore, a quasi-stationary positive electric field was observed at x ~ 0.8 μm. This corresponds to a thermal electric field revealed near the front due to electron non-local heat transport associated with a steep pressure gradient [6]. Namely, energetic tail electrons heated by non-local thermal conduction lead to ionization to C^{5+} and, finally, C^{6+} through impacts and trigger the propagations. Note that we have excluded the recombination process in the present simulation, but the ionization dynamics for C^{5+} and C^{6+} may be affected by the process in the downstream region where the temperature is low.

In conclusion, the ionization dynamics in solids is found to evolve through multiples stages with different time scales.

[1] D. Umstadter, Phys. Plasmas **8**, 5 (2001).
[2] Y. Kishimoto, Annual Report of the Earth Simulator Center, Apr.'03-Mar.'04, p.199 (2004).
[3] M.V. Ammosov *et al.*, JETP **64**, 1191 (1986).
[4] K. Kim *et al.*, Phys. Rev. A **50**, 3954 (1994).
[5] S. Ichimaru, *Basic Principle of Plasma Physics*, (Benjamin, Inc. 1973) p.62.
[6] Y. Kishimoto *et al.*, J. Phys. Soc. Jpn. **57**, 1972 (1988).