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Ionization dynamics in laser-matter interaction
レーザー物質相互作用における電離ダイナミックス

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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 the field ionization due to the induced plasma wake, and a slow time scale global ionization beyond whole spatial region with C^{5+} and C^{6+} triggered by electrons impact ionization due to heated hot electrons. The plasma wave is found to be self-sustained by the pressure gradient of the propagating ionization front.

1. Introduction

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 a priori assumption of 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.

2. Simulation parameter

Here, we carry out one-dimensional simulations in a box of size L_y = 2.46μm, where carbon film with 1/20 of solid atom density, i.e. $n_i = 0.88\times10^{22}$ cm^{-3}, is set in 0.41μm < y < 1.23μm. A p-polarized laser is emitted in the x-direction from the antenna placed at y=0.04 μm. Here, we employ a transparent boundary condition in the x-direction. The laser parameters consist of a wavelength of λ = 0.82μm, 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 ADK [3] and the BEB formula [4]. The relaxation process is modeled by the Monte-Carlo method via successive binary collisions of particle pairs.

3. Numerical results

The time histories of ion abundance for each charge state C^{q+} are shown in Fig. 1. After the laser pulse hits the film, ionizations are successively triggered from C^{1+} to C^{2+}. The charge state q = 4 evolves slowly at first, but found to be suddenly accelerated around t = 23fs. The abundance of C^{1+}, C^{2+}, and C^{4+} shows clear linear dependences with time. On the other hand, the number of C^{5+} and C^{6+} increases with time, but the rate is small compared with that for C^{4+}. Furthermore, the number of C^{5+} and C^{6+} ions gradually increases even after the direct interaction with the laser pulse has ceased.

Figure 2 shows the electron charge density profiles ($\Sigma_j q_j n_j/en_0$) at different time scales after t=10 fs, i.e., panel (a) shows profiles from 10.7fs to 23.5fs, (b) from 23.5fs to 33.8fs, (c) from 34.6fs to 68.8fs, respectively. 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. It is found that the charge state up to C^{2+} is produced directly by the laser field which initially propagates inside the carbon film since the film is initially neutral. From the localized high density region near the surface, the ionization for C^{4+} starts as seen in Fig. 2 (a), but the evolution is slow as also seen in Fig. 1. However, around t= 23fs, the front of C^{4+} starts to convectively propagates deep inside with higher speed and reaches the rear side (t=33.8fs), 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.1 corresponds to an ionization front to the charge state q = 4.

Figure 3 shows the coordinate of ionization front C^{4+} as a function of time. It is clearly seen that the front speed is changed at t ~ 23fs from 2×10^7 m/s to 1.17×10^8 m/s (roughly 1/3 of the speed of light). The speed is also found to be accelerated to 1.68×10^8m/s around t=29 fs. Followed by the propagation of C^{4+}, ionizations to higher charge states, i.e. q = 5 and q = 6, are proceeded, but the dynamics is different from that of C^{4+}, i.e. the charge states gradually increase in whole region from the front to rear side.

We investigated the ionization process for each electronic state of carbon ions. We found that the ionizations up to q=4 were 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 illustrate the spatial distributions of the ion charge density (ρ_i) and longitudinal electric field E_y at t = 25 fs (a) and t = 32 fs. As can be seen, the oscillating electric fields which propagates with the ionization front with a similar speed are found to be excited, suggesting that the ionization for C^{4+} results from this field. It is possible to conclude that the observed longitudinal electric field is the propagating plasma wave, i.e. wake field. As is well known, the wake field is generally excited by the spatially localized laser field. However, the laser field does not exist inside the film due to the higher density than the cut-off. From the detailed analyses of the simulation, we found that the wake field is excited by the density gradient of the ionization front due to its steep pressure gradient, which plays a similar role as that of photon pressure of the laser field. Namely, the ionization front of C^{4+} is self-sustained such that the front ionization is proceeded by the plasma wake, but it is excited by the pressure gradient at the ionization front.

4. Summary

In conclusion, the ionization dynamics in high density carbon medium is found to evolve through multiples stages with different time scales. The field ionization sustained by the plasma wake found to play an important role leading to fast convective ionization.

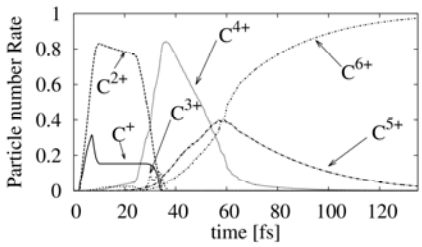

Fig.1 Time history of ion abundance for each

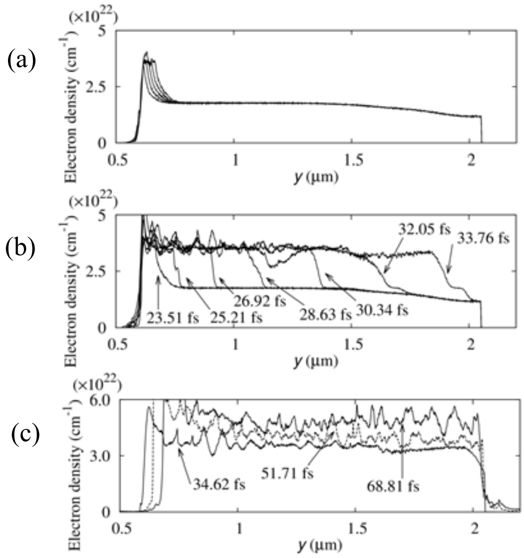

Fig. 2 Electron density profiles

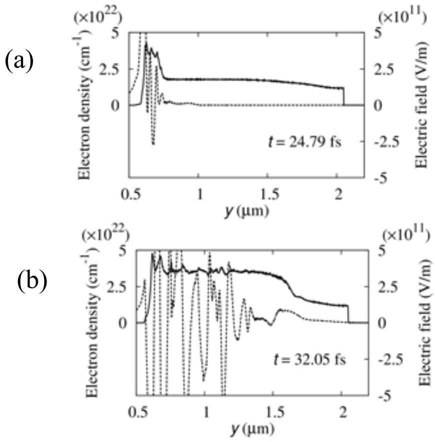

Fig. 3 Electron density and longitudinal electric field profiles at (a) t=24.79fs and (b) 32.05fs

References

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