

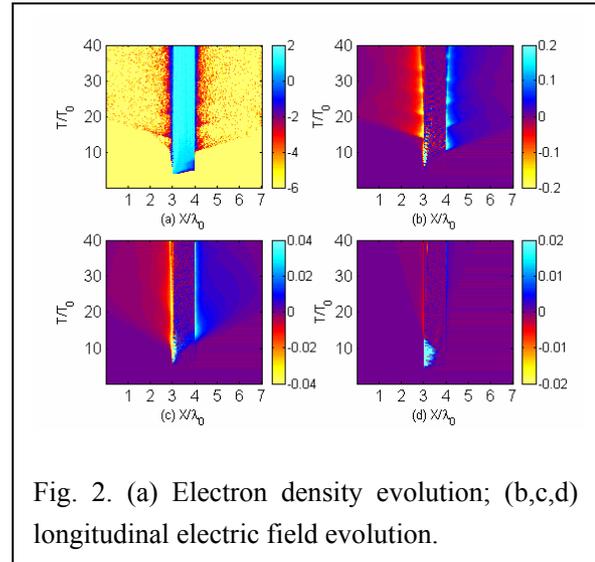
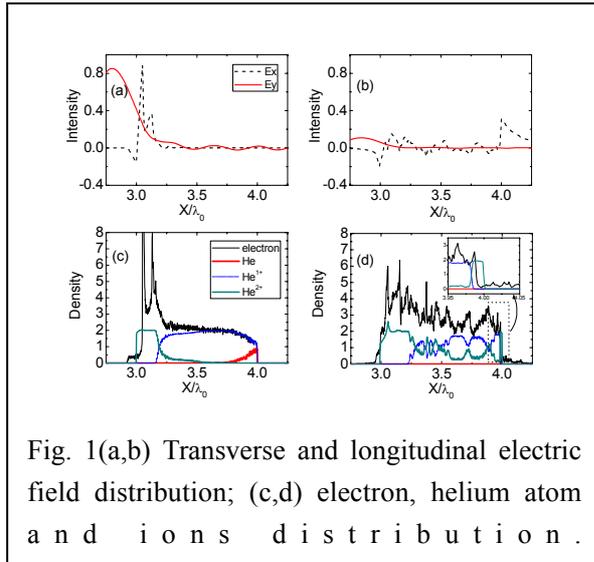
Acceleration of electrons and ions in the interaction of high-intensity lasers with dense gaseous targets

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In recent years, particle acceleration by ultra-short intense laser plasma interaction has attracted extensively attention. For under-dense plasma, many kinds of acceleration projects have been proposed such as laser wake field acceleration[1-6], betatron acceleration[7,8], stochastic acceleration[9] etc. However for over-dense plasma, because of the opacity of laser pulse, only particles accelerated in front of the material have been widely studied[10]. But little attention has been paid to the particles transmitted into the material. In this paper, we studied the ultra-short intense laser pulse interaction with an over-dense gaseous foil. Both the particles accelerated in front and behind of the target are considered. We found that for different laser intensity and gas density, there are three different interaction scenarios for the energy exchange among electrons, ions and longitudinal electric field, corresponding to different electron trajectories. Special attention has also been paid to the accelerated ions. At certain conditions, the ions can be even more effectively accelerated inside the target than those at the target surfaces.

Unlike usual theoretical simulations, we used a target initially composed of neutral atoms and it will be ionized when the laser irradiates it. To do this, we add the field ionization[11] subroutine in our one dimensional particle in cell code. Because of the over-dense target, impact ionization and two body collisions are also included in our code. To deal with the energy loss by ionization we adopt virtual currents method to compensate the ionization energy just as Kemp *et al* has done[12]. A 800nm, 26.7fs laser pulse is normally injected into the target from the left boundary of the simulation box which is 7 laser wave length long. The laser electric field is $E(t) = a_0 \sin^2(\pi t/T)$, where a_0 is the peak value of the field normalized by $mc\omega/e$, ω is the laser frequency, m and $-e$ are the electron mass and charge,



respectively. The target is made of He and is $1\lambda_p = 0.8\mu\text{m}$ thick located in the center of the simulation box. Firstly, we studied the interaction of a laser pulse of intensity $a_0 = 0.5$ with helium target of density $n_0 = 2.0n_c$, here $n_c = 1.7 \times 10^{21} / \text{cm}^3$ is the critical density.

Figure 1(a, b) show the longitudinal and transversal electric fields after the laser pulse has propagated 8 and 12 laser periods from the left boundary; (c, d) show electron, He, He^{1+} and He^{2+} density at the same time. As we can see because of initially neutral atoms, the electrons ionized by the laser field in the front surface of the target are pushed into the target and make longitudinal maximum electric field inside the target. Then both the transverse and longitudinal electric fields contribute to generate He^{2+} . At $12T_0$, the laser field is weaker than the longitudinal field which gets two maximum value at the surfaces of the target. Fig. 1(d) shows that the He^{2+} particles at the rear surface are produced by the longitudinal static field. In a compared simulation, we switch off the impact ionization subroutine, it shows there is no obvious difference for the ionization state at the two surfaces of the target, but the He^{2+} does not appear inside the target in this case. It shows the field ionization dominates at the surfaces of the target but impact ionization dominates inside the target. Figure 2(a) and (b) show the temporal evolution of electron density and longitudinal electric field, respectively. It is obvious that the electrons are periodically ejected out of the target and the maximum value of the longitudinal field also alternately appears at the two surfaces of the target. To clear this kind of ejection, we use the electron's positions at $11T_0$ as the transverse coordinate and use

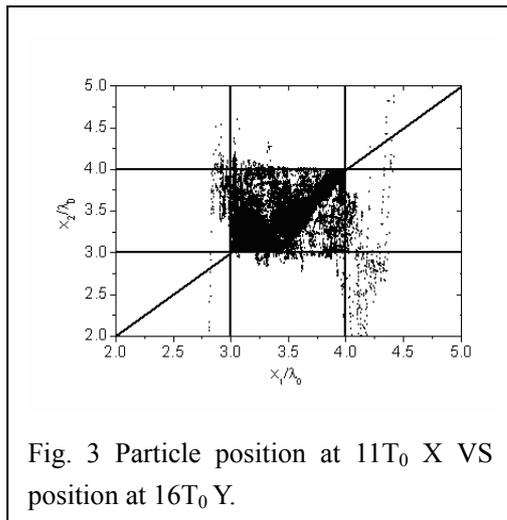


Fig. 3 Particle position at $11T_0$ X VS position at $16T_0$ Y.

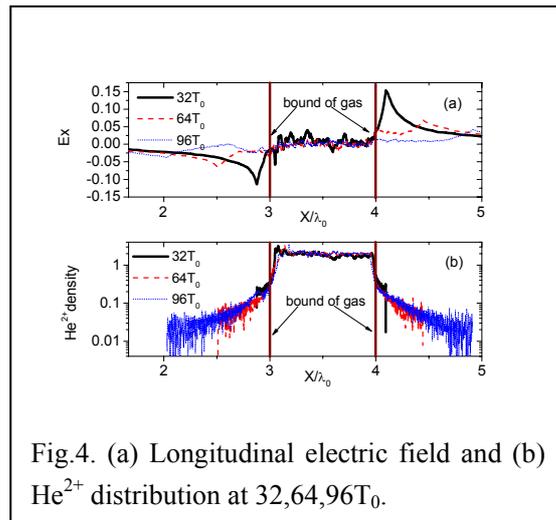


Fig.4. (a) Longitudinal electric field and (b) He^{2+} distribution at $32,64,96T_0$.

their positions at $16T_0$ as longitudinal coordinate to generate Fig. 3. As it shows some electrons originally behind the target ($x > 4.0\lambda_0$) move to the front of the target ($y < 3.0\lambda_0$). We also check the new born electrons during this time, all of them are inside the target. So the periodical ejection of electrons is because of the oscillation of the high energy electrons between the target two surfaces. Correspondingly the longitudinal fields alternately get their maximum value. Fig 2(b) shows that the peak of the longitudinal moves outside as time goes on. It is because the He^{2+} particles move outside just as Fig 4 shows. The He^{1+} particles do not go out side because its lower value of charge to mass ratio.

In another simulation, we change the laser intensity to $a_0 = 0.3$ and keep the gas density $n = 2.0n_c$. Fig. 2(c) shows the temporal evolution of longitudinal electric field in this case. As we can see there is no periodical ejection of electrons and the maximum value of longitudinal electric field does not oscillate. It is because that the laser is not strong enough to generate

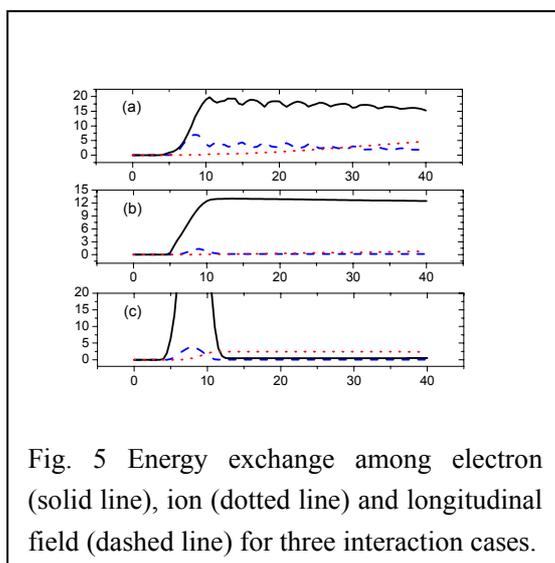


Fig. 5 Energy exchange among electron (solid line), ion (dotted line) and longitudinal field (dashed line) for three interaction cases.

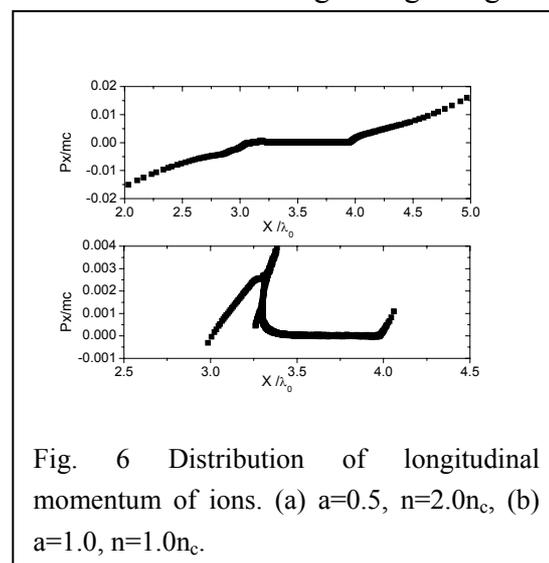


Fig. 6 Distribution of longitudinal momentum of ions. (a) $a=0.5, n=2.0n_c$, (b) $a=1.0, n=1.0n_c$.

large amount of hot electrons which in turn make a strong static charge separation electric field at the target surfaces. So the electrons can not be dragged back to the target and oscillate between the target surfaces. For an intense laser ($a_0 = 1.0$) and low gas density ($n = 1.0n_c$) condition, we have found that all the electrons and ions move inside. The laser accelerates the ions directly and the cold electrons move with the ions. The longitudinal electric field in front of the target is quite small as shown in Fig. 2(d). The energy exchange among electrons, ions and longitudinal electric field are shown in Fig. 5 for the above three cases. In the first case, along with the oscillation of electrons between the target surfaces, the energy also oscillates among electrons, ions and longitudinal electric field. In this way the ions get some energy from the fields. In the second case, the longitudinal fields are not so strong and there is no obvious ion acceleration. In the third case, ions can be accelerated directly by the laser ponderomotive force. Fig. 6(a, b) shows the relationship between longitudinal momentums and positions of the ions (He^{1+} and He^{2+}). As it shows in the first case the ions are accelerated by the static charge separation electric field, however, in the third case ions get more acceleration inside the target than the target surfaces but this acceleration is not so effective as the first case.

In conclusion, the electrons dynamics can be quite different under different conditions of laser intensity and gaseous foil density. It makes the energy exchange among electrons, ions and longitudinal electric field also different. For an intense laser pulse interaction with a low density gaseous foil, ions can be accelerated inside the target more than outside the target.

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