Laser-plasma ion acceleration

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Abstract

Multiple-charged ion acceleration from a plasma slab irradiated by an intense, short laser pulse is studied via the collisional particle-in-cell simulation including various mechanisms of plasma ionization. The forward ion acceleration by the shock wave produced by the *ExH* force, the bluster-type ion acceleration, is found to be very efficient. Effect of contamination on the forward and backward ion acceleration is analyzed.

1 Introduction

Plasmas irradiated by a short pulse laser can be an efficient, compact, and flexible source of MeV protons as well as highly charged MeV ions. Hot electrons produced by the laser pulse irradiating a solid target drive ion emission. Due to highly anisotropy distribution of the hot electrons, the emittance of a source of energetic ions is comparable to that of ion beams produced via electrostatic acceleration. This has been demonstrated through numerical kinetic simulations [1] and recent experiments [2-4]. There are three principal mechanisms of ion acceleration from solids irradiated by a short laser pulse, see Fig. 1. The

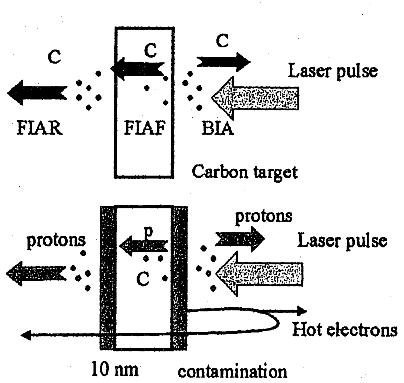

Figure1: Various mechanisms of ion acceleration

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first is the backward ion acceleration (BIA) driven by the hot electrons from the front side of the target toward the laser pulse. The second is the forward ion acceleration (FIAR) from the rear side of a slab target dominated by hot electrons penetrating through the slab. The third is the forward ion acceleration by the shock wave produced by the relativistic acceleration force (*ExH*) from the front side of the target [5] (FIAF). The efficiency, maximal ion energy, and emittance of ion acceleration vary differently with the laser intensity, pulse duration, and plasma density for different acceleration mechanisms.

Contamination may have a strong effect on the ion acceleration. If no special measure made, the contamination layer has usually 10 nm thickness. The contamination consists of water absorbed from the atmosphere. Since the charge-to-mass ratio is the largest for protons, these particles are mostly accelerated by hot electrons in either direction. To produce effective ion acceleration, the surface cleaning should be performed.

In the present work, we investigate numerically various mechanisms of energetic ion emission from slab targets irradiated by an obliquely incident picosecond pulse laser, as well as very intense subpicosecond pulse lasers and effect of contamination on these mechanisms. We use the collisional PIC simulation employing the average ion model to include transient plasma ionization. Effect of plasma induced field ionization on the FIAR is studied. By applying the Langevin equation, we make the method conformed to direct Fokker-Planck simulation.

2 Ion acceleration mechanisms

The BIA dominated by the electrostatic field generated due to hot electrons produced via the resonance absorption is quite efficient for moderate laser intensity. Calculations show with total laser absorption efficiency over 40%, about 10% of the laser energy can be funneled into ion acceleration over 1 MeV, which corresponds to more than 10^{11} fast ions per pulse with 10 TW, picosecond Ti-Saph laser. The emittance of such beams can be about 1-2 π mm mrad. With the laser intensity I, the maximal ion energy increases as $I^{1/2}$. However the plasma corona produced by the laser prepulse can strongly affect on the emittance due to electric fields after the laser pulse as well as the magnetic field. The FIAR process appears in slab targets with the thickness that is less than the hot electron free path. In that case, the hot electrons penetrating the target and maxwellizing at the rear side of the target drive the forward ion emission. Due to the very directed velocity distribution of those electrons, the emittance of ions is better than that of BIA. The efficiency of the FAIR depends on the laser intensity and target thickness. If the free path of an electron with the energy $\sim T_h$, the temperature of hot electrons, is less than the target thickness, the efficiency of FIAR is comparable with that of BIA. The maximal ion energy increases as $I^{1/2}$ with the laser intensity as well. In contrast to FIAR and BIA, the FIAF strongly depends on plasma density. Under action of the laser pulse, the positively charged layer with the thickness $d\sim 1/N_e$ is formed at the front surface of the target. The maximal energy of forwardly accelerated ions equals to the potential difference at this layer $\Phi\sim N_e d^2\sim 1/N_e$. In solid density plasmas, the maximal energy of FIAF is comparably small. The efficiency is much smaller than that of BIA. Since FIAF' ions have to pass through the target, their emittance is much worse than the emittance of BIA and FIAR. The typical velocity distribution of ions emitted from a foil irradiated by subpicosecond laser pulse is shown in Fig. 1. One can see that the maximal ion energy of FIAR is much higher than those of FIAF and BIA. In the case of BIA, the hot electrons, which dominate ion acceleration, are decelerated by *ExH* force suppressing the ion acceleration. The small maximal energy of ions from FIAF is a result of the steep density gradient at the front size of the target.

Nevertheless, the FIAF mechanism can become important if the plasma corona with low density is formed at the target surface due to the laser prepulse. In that case, the potential difference gets very large and the energy

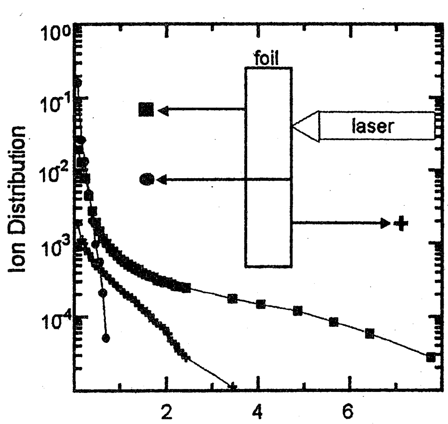

Figure 2: The typical velocity distribution of accelerated ions from a foil irradiated 100 fs laser pulse of 10^{19} W/cm^2

acquired by ions can be comparable or even higher than that of FIAR ions. The shock wave produced by *ExH* force has complicate structure. After passing through the density maximum, the shock wave divides into several solitons. The number of solitons depends on the laser intensity and plasma density. When the background plasma becomes underdense, the overdense solitons (ion bunch) can be further accelerated by the *ExH* force to energy considerably higher than the maximal energy of the FIAR. The spatial distribution of density and velocity in the ion bunch are shown in Fig. 2 and Fig. 3 for several time points. The acceleration by the *ExH* is clearly seen. After 3 ps, the Al ions acquire 50 MeV energy. Since the *ExH* force is very directed, the ion bunch must have a very low emittance.

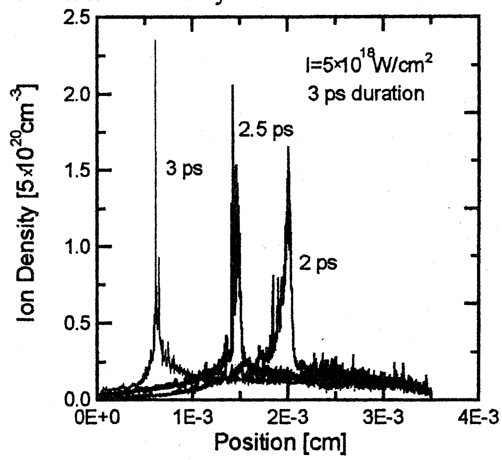

Figure 2: The ion density distribution in an C plasma irradiated by 3 ps laser pulse with intensity of 5×10^{18} W/cm^2, λ=0.8 mm

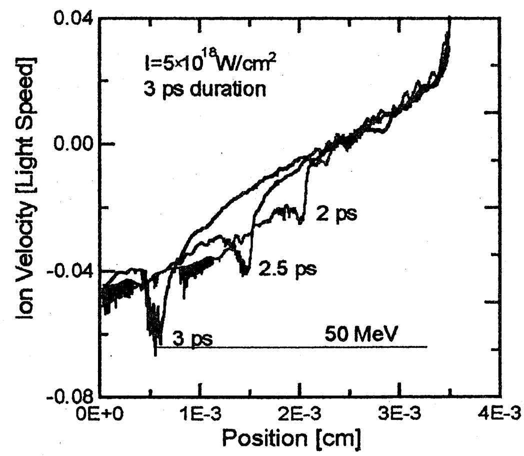

Figure 3: The temporal evolution of the velocity distribution in the ion bunch in the C plasma.

In long pulse (>100 ps) laser-produced plasmas, electron inelastic collisions are the main cause of ionization. However, if the duration of a laser pulse is short (<1 ps), although the plasma is heated rapidly, highly charged states inside the bulk plasma cannot be produced because the collisional ionization time increases as $I_Z T_e^{1/2}$, where I_Z the ionization potential and T_e the electron temperature. Moreover, since the rate of collisional ionization is proportional to the density, the ionization occurs only in the high density plasma bulk. In the plasma corona the rate becomes negligibly small.

In the presence of an intense laser pulse the optical field ionization (OFI) becomes important on the plasma surface. The ionization in the backward expanding plasma corona is sustained as long as the laser field is present. The maximal charge of ions created by OFI may be estimated from the field ionization probability,

$$\nu_E = 4\omega_A \left(\frac{I_Z}{Ry}\right)^{5/2} \frac{E_A}{E_L} \exp\left(-\frac{2}{3}\left(\frac{I_Z}{Ry}\right)^{3/2} \frac{E_A}{E_L}\right)$$

and t the pulse duration satisfying the condition $n_E(I_Z)t=1$, where I_Z is the ionization potential for ion with charge z, $E_A=m^2e^5/h^4$ the atomic field, $\omega_A=me^4/h^3$ the atomic frequency, $Ry=m^2e^4/2h^2$, E_L the laser electric field. By solving this equation we find the maximal potential I_Z which is approximately

$$I_Z = Ry\left[\frac{E_L}{E_A}\left(23+\ln(\tau/100\text{fs})+\ln(E_L/E_A)\right)\right]^{2/3}.$$

As the laser intensity rises from 10^{19} to 10^{21} W/cm^2, the potential increases from 1 keV to 5 keV for the 100 fs pulse duration. For example, this potential corresponds to ionization potentials 21^+ and 38^+ ions of Zr (Z=40) respectively. The collisional ionization time (>1 ps) for such ions is much greater than the laser pulse duration even in the plasma bulk. Furthermore, the electric field of the laser exists only within the thin skin layer near the target surface. Within the conventional theory, it is unable to have fully ionized ions at the rear side of the foil. However, the field ionization can occur at the rear side of the thin foil [6]. In the present study, the typical foil thickness is d~(0.1-1)l, which is less than the excursion length of hot electrons and greater than the skin depth. Hot electrons accelerated into the bulk by the ponderomotive force give rise to electrostatic fields on the foil surfaces. Under this condition, the electrostatic field at the rear side of the target can, in one dimension, be estimated via Poisson's equation,

$$E_{rear}=4\pi eN_h d,$$

where $N_h=\eta N_c v_0/v_T$ is the density of hot electron, η the absorption efficiency, N_c the critical density, v_0 the electron quiver velocity, v_T the thermal velocity of plasma electrons. Under condition discussed, the hot electron density approximately equals to the critical density and the electric field $eE_{rear}/mc\omega\sim\omega d/c$ is of the same order as the laser field. The spatial distribution of the electric fields in the case of a Ti foil is shown in Fig.2 for t=80 fs. The strength of the calculated electrostatic is close to the estimation. Thus, at the rear side of the foil, the plasma induced field ionization (PFI) becomes significant and as efficient as OFI. The maximal ionization potential is up to 600-800 eV for the laser intensity over 10^{19} W/cm^2. Since ions leaving the plasma bulk are further ionized by this field, they acquire grater charges and energies.

Typical charge distribution of ions emitted from the foil irradiated by a short laser pulse is given in Fig. 5 Due to OFI, the ions emitted from the front surface are fully ionized, while ions emitted from the rear surface are not. However, the plasma induced field ionization increases considerably ion charges so that carbon nuclei and H-like ions are mainly presented. The calculation performed for carbon slab target with 10 nm contamination layers in either side shows no ion acceleration; only energetic protons are observed.

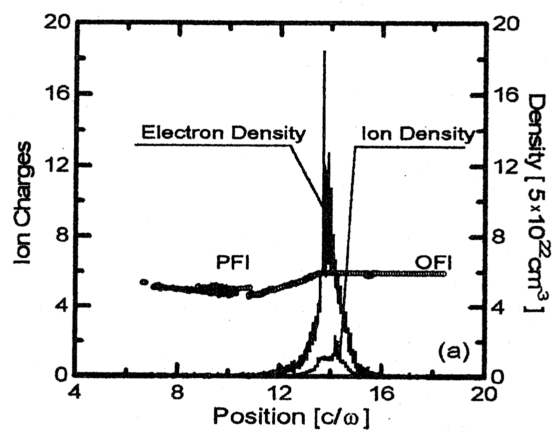

Figure 5: The spatial charge distribution in a carbon foil of 200 nm thickness irradiated by I=4x10^{19} W/cm^2 λ=800 nm, t=80 fs pulse laser at t=100 fs.

Conclusion

We have studied efficiency of various mechanisms of ion acceleration from plasmas irradiated by an intense, short laser pulse in overdense plasmas by the collisional particle-in-cell simulation including plasma ionization and contamination effects. The bluster like ion acceleration, is found to be efficient and to have a low emittance. We believe that effects of contamination and ionization delay can be reduced for this mechanism of ion acceleration.

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