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Emission of MeV multiple-charged ions from metallic foils irradiated with an ultrashort laser pulse

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From full kinetic particle-in-cell simulation including elastic collisions and collisional and field ionization, we find that the emission of MeV multiple-charged ions from a non-low-Z matter foil irradiated by a short laser pulse sensitively depends on the ion charge distribution. In spite of strong elastic collisions, the anisotropy of the hot electron velocity distribution enhances the ion energy and improves the emittance. With up to 10% conversion of the laser energy, Al^{+6}-Al^{+7} ions over MeV energy are produced from 0.125μm foil with an obliquely incident (45°) p-polarized laser pulse of 1 ps duration in the range of intensity 10^{16-17} W/cm^2.

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During the interaction of an intense short laser pulse with a solid target a considerable portion of multiple-charged ions driven by superthermal electrons can be accelerated over MeV energies [1–5] as in the case of proton acceleration [6–10]. These high energy ions have a variety of applications from ion implantation to a source for nuclear experiments. Especially, experimental studies of the excitation of low-lying (1–20 keV) isomeric nuclei levels [11,12] and stimulation of resonance reactions with a few MeV threshold in short-lived nucleus [13] can be realized with the laser plasma ion source using a table-top size facility.

The emission of energetic protons from laser-produced plasmas has been explored experimentally in the laser fusion study [6], as such emission significantly decreases the efficiency of the pellet compression. The strong correlation between the highest proton energy and temperature of the hot fraction of plasma electrons has been found through many experiments [7]. Theoretically, this process has been considered as the plasma expansion driven by hot electrons in the framework of fluid dynamics for a slab target [7,14–18]. The two ‘‘temperature’’ exponential distribution of electrons has been introduced in order to treat nonequilibrium effects [16,18]. More specifically, assuming the plasma quasineutrality, a superposition of two self-similar solutions for the ion density has been obtained in Ref. [16],

$$N(\nu,t)=A\exp(-\nu/C_c)+B\exp(-\nu/C_h). \qquad (1)$$

Here $C_c=(zT_c/M)^{1/2}$, $C_h=(zT_h/M)^{1/2}$ are the ion sound speeds with the ion mass M and charge z. T_h and T_c are temperature of hot and cold electrons, respectively. A and B are the constants dependent on the heuristic parameters: T_h, T_c, and fraction of hot electron, f_h. The analytical velocity distribution (1) derived in [16] becomes singular at $v\sim(1-2)C_h$ if the ratio T_h/T_c exceeds 9.9. To overcome this problem, the use of a truncated bi-Maxwellian distribution with the maximal electron energy $\varepsilon_{\max}\sim(1–3)T_h$ has been suggested in Ref. [18]. A strong dependence of the ion velocity distribution on $\varepsilon_{\max}$, and T_c, T_h, f_h has been derived. However, the maximal electron energy has not been observed, at least up to $(6-8)T_h$, in the recent bremsstrahlung measurements [8,19] of metallic targets. This shows the limitation of the applicability of the fluid approach in a study of the emission of multiple-charged ions.

We are interested in the multiple-charged ion emission from foil targets irradiated by a short pulse laser of moderate intensity $I\lambda^2=10^{16-17}$ Wμm^2/cm^2. In this regime we need full kinetics simulation. Since the energy of emitted ions is proportional to their charge z, the ionization dynamics is a crucial part of the ion acceleration. So far, particle-in-cell (PIC, [20]) calculations for the ion emission have been made only for short laser pulses with relativistic intensity $I>10^{19}$ W/cm^2 [1–4]. In the pioneering works [1–4] ions have been assumed to be fully ionized which might be reasonable for low-Z targets irradiated by very high intensity laser pulse. However, at the moderate intensity of a short laser pulse, non-low-Z matters cannot be instantaneously stripped to the fully ionized state and hence the transient plasma ionization needs to be considered in the emission process. In this Rapid Communication we show the emission of MeV ions with the energy conversion efficiency up to 10% from both sides of a thin foil with thickness much less than the hot electron excursion length, irradiated by a laser in the range of 1 ps pulse duration, obliquely incident p-polarization at intensity of 10^{16-17} W/cm^2.

The process of ion emission from a plasma irradiated by a short laser pulse can be subdivided into two stages. First, ions are accelerated by the charge separation field as suggested by Gibbon [21]. This field develops due to hot electrons produced by the vacuum heating [22] inside a layer on the target surface with a thickness of $x\sim(\Phi/2\pi eN_e)^{1/2}$, where Φ is the ponderomotive potential due to the laser pulse. Second, as the temperature of the bulk plasma increases, the density gradient is formed and the electrostatic field penetrates into the plasma. This process leads to a self-similar expansion of the bulk plasma, which accelerates ions sustaining density gradient at the critical point (0.1–0.2)λ for the high rate of the resonance absorption. Then, the ratio of conversion from electrons to the accelerated ions in the bulk is

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$$\kappa \equiv \frac{\langle N_i \rangle \langle \varepsilon_i \rangle}{\langle N_e \rangle \langle \varepsilon_e \rangle} = \frac{MC^2}{azT}, \quad (2)$$

where $\langle N \rangle$ and $\langle \varepsilon \rangle$ denote the average number of particles and their energy and C the ion sound speed, T the electron temperature, a is a coefficient determined by the ratio of the total electron energy to their temperature. Eq. (2) shows in the case of the isotropic velocity distribution $a=\frac{3}{2}$, the conversion ratio $\kappa=0.67$, that becomes $\kappa=2$ for a fully anisotropic electron distribution with $a=\frac{1}{2}$.

Electrons heated as a result of wave breaking have strong anisotropy in their velocity distribution, leading to an increase in conversion efficiency of laser energy to ions. Finally, in the case of a thin foil target, the ion acceleration becomes an effective mechanism of electron cooling and the total absorption may be as high as that of solids, up to 70% [23,24]. Again, the ionization on the plasma surface can strongly influence the absorption rate and ion emission via the rate of formation of a plasma shelf [21,25] and resulting energy of accelerated ions. A hybrid PIC simulation, one-dimensional in the space and three-dimensional in the velocity space, is employed, incorporating the non-local-thermodynamic-equilibrium (non-LTE) ionization and adopting the Langevin equation to account for elastic collisions. Electron-electron, electron-ion, and ion-ion collisions are incorporated in the nonlinear Langevin equation [25]. Thus this simulation can model the entire process of ion emission from a thin metallic foil irradiated by an obliquely incident picosecond pulse laser.

In Maxwell equations we modify the Bourdier boost reference technique [21] to operate in the laboratory frame of reference, to account for collisional absorption, vacuum heating, anomalous skin effect, and resonance absorption for obliquely incident laser light. Plasma ionization and its temporal evolution are considered by calculating the charge of computational particles (CPs). Simple atomic kinetics based on the average ion model [26], in which the ionization potential I_z is a function of ion charge z, is used to calculate the charge. Namely, the change of plasma electrons is calculated by the electron balance equation (25) that includes the electron collisional ionization and the field ionization in the presence of the intense laser light,

$$\Delta Q_{ek} = \Delta t N_z \left[-Q_{ek}(R_z N_e) + \sum_{\varepsilon_l > I_z} q_l \nu_l \sigma_z(z) - \frac{e \Delta x}{\tau(I_{z+1}, E_k)} \right], \quad (3)$$

where Q_{ek} is the total electron charge in the kth cell, q_l is the charge of lth CP which belongs to the kth cell with the size Δx, Δt the time step, σ_z the collisional ionization cross-section, and R_z the three-body recombination rate. We use the field ionization probability τ^{-1} obtained in Ref. [27] with E_k being the electric field averaged over the kth cell. Electrons acquire the charge $\Delta Q_{ek}/N_{ek}$ and ions $-\Delta Q_{ek}/N_{ik}$, where N_{ek} and N_{ik} the number of particles in the kth cell. While the electron charge-to-mass ratio is kept constant, the ion is increased with z. To compensate the energy loss due to the optical field ionization (OFI) Q_{OFI}, we include the effective atomic current to the Maxwellian equation so that

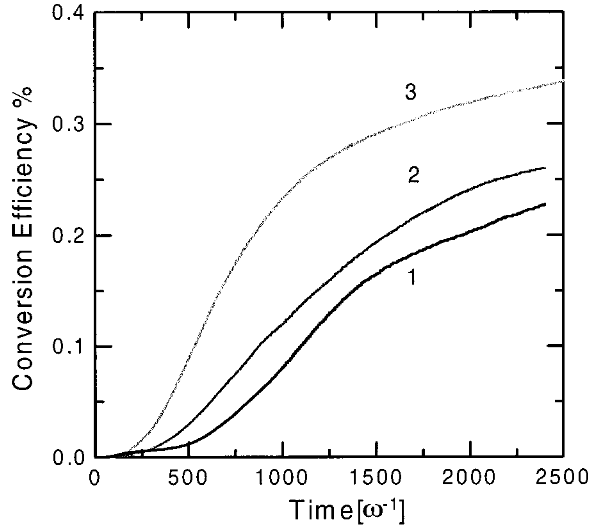

FIG. 1. Temporal evolution of the efficiency of conversion of the laser energy to ions. An aluminum foil ($d=125$ nm) irradiated by an obliquely incident (45°) laser pulse ($I=4\times10^{16}$ W/cm^2, $\lambda=800$ nm), for the plasma with (1) and without (2) elastic collisions. (3) the plasma with fixed ion charges $z=10$. The total absorption efficiency is 47%, 36%, and 48%, respectively.

$j_A(t)\mathbf{E}_L(t-\Delta t)=Q_{\mathrm{OFI}}(t-\Delta t)$ [28] with $\mathbf{E}_L$ the laser electric field. The energy loss due to the collisional ionization is calculated as an effective friction. We use a kinetics grid to determine the plasma parameters. As the scale length of the change of the charge is mainly determined by the electron mean free path rather than Debye length, approximately 20 PIC cells are combined to form a kinetics cell. It also provides statistics in calculation of the temperature, density, and fluid velocity. This model has been checked via the kinetic simulation of laser-irradiated carbon and silicon overdense plasmas [25].

The calculation is carried out for the picosecond pulse laser irradiation of an 125 nm thick aluminum foil. The initial temperature of the plasma is 10 eV and N_i is set to the solid density. The initial ion charges are calculated by the Saha equation. The laser intensity is kept constant during the laser pulse of 1 ps duration. The time step is set to $0.1/\omega_p^0$, where ω_p^0 is the initial plasma frequency. The number of CPs representing plasma electrons is 3×10^4. To understand the effect of collisions and ionization, the usual PIC calculation without collisions and with the simplest plasma ionization model assuming ion charge $z=10$ which corresponds to the LTE with the plasma temperature of 1 keV is also performed.

The temporal evolution of the efficiency of laser energy conversion to ions is shown in Fig. 1. While in the plasma with transient ionization the conversion rate is approximately 25% with the total absorption efficiency of 47% in collisional and 36% in collisionless plasmas. The PIC calculation with a fixed charge of $z=10$ gives a significantly higher conversion rate to ion, over 35% with the total absorption of 48%. So that the fixed charged model leads to overacceleration of fast ions. The total absorption rate is saturated at 0.42 ps $\sim 1000/\omega$ after the formation of the plasma shelf with the density gradient scalelength of $L\sim0.1\lambda$ at the critical point. In all plasmas considered after the saturation the conversion

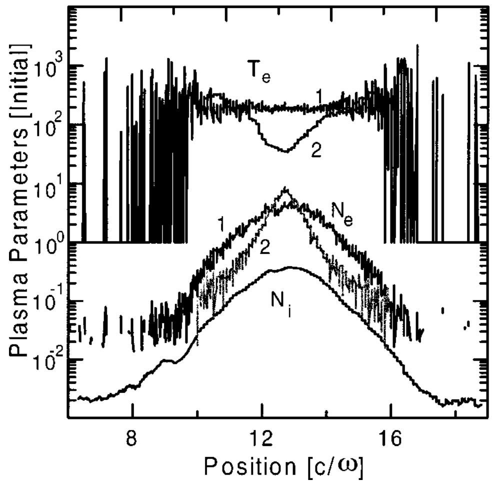

FIG. 2. Spatial distribution of Al foil plasma parameters, for an obliquely incident, 45°, p-polarized pulse $t=0.8$ ps. $I=4\times10^{16}$ W/cm^2, $\lambda=800$ nm. The electron temperature and density are given for plasma with elastic collisions (1) and without (2).

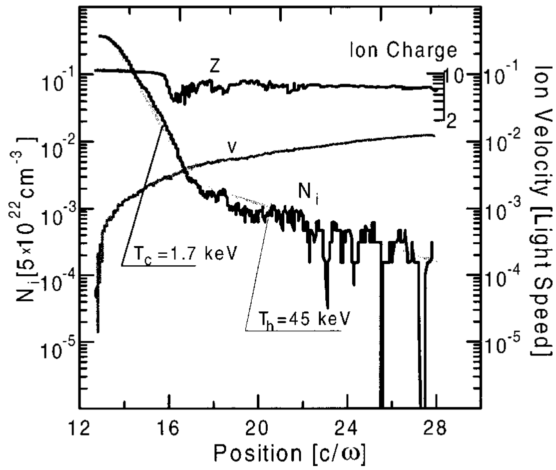

FIG. 3. Spatial profile of backwardly accelerated ions at $t=0.8$ ps. Exponents correspond to the approximation given by Eq. (1) with adjusted temperatures.

to ion acceleration surpasses the net electron absorption. This coincides with the appearance of the electric field in the entire plasma due to the ion density gradient, which leads to the consequent ion acceleration characterized by the self-similar expansion. By inserting the calculated efficiency in Eq. (2) we find that $\kappa=1$ in the collisional plasma. We also find from the distribution that only the hot electrons have the anisotropy, as the collisional relaxation is less effective for electrons having higher energies, which significantly increases the efficiency of laser energy conversion to fast ions.

The instantaneous ($t=0.8$ ps) plasma conditions are shown in Fig. 2. The electron temperature is uniform in the bulk of collisional plasma, while it has a spatial minimum in the plasma without elastic collisions. The temperature of the collisional plasma slowly changes from 1.5 keV at $t=0.5$ ps to 1.9 keV at $t=0.8$ ps, reflecting the reduction of the net electron heating. The calculated temperature of hot electrons is close to that from well-known empirical formula [29,30]

$$T_h=30(I\lambda^2/10^{17}\ \ \mathrm{W}\mu\mathrm{m}^2/\mathrm{cm}^2)^{1/3}(T_c,\ \ \mathrm{keV})^{1/3}\ \ \mathrm{keV}.$$

The electron density in the plasma without elastic collisions is spikier than that of the collisional plasma and far from the self-similar density profile. Inside the foil, Al^{+11} and Al^{+12} are produced by the collisional ionization during rapid heating in the solid density bulk. On the other hand, in the coronal plasma, as the ionization time becomes significantly longer in low density, only Al^{+6} and Al^{+7} appear even the electron temperature is higher. Furthermore, in the present condition, the rate of OFI is smaller than those of the collisional ionization. The ionization potential of the highest charge state, which may be produced in the presence of a laser field E_L, is estimated by solving equation $\tau^{-1}(I_Z,E_L)\delta t=1$, with ionization probability τ^{-1} determined by the Landau formula (see [27]) and δt the pulse duration. An approximate solution is

$$I_z=Ry\left[\frac{E_L}{E_A}[23+\ln[\delta t/(100\ \ \mathrm{fs})]+\ln(E_L/E_A)]\right]^{2/3},$$

where Ry$=13.6$ eV and $E_A=m^2e^2/\hbar^4$ the atomic field. For $I=4\times10^{16}$ W/cm^2, this gives the ionization potential I_z that corresponds to Al^{+3}-Al^{+4}. The charges of forwardly accelerated ions are only slightly smaller than that of backwardly accelerated ones because the collisional ionization is still dominant for moderate laser intensities and the effect of plasma induced field ionization [31] is still negligible. The spatial minimum of charge of emitted ions is a result of the ion mobility change with their charge z.

The spatial distribution of ionic quantities is shown in Fig. 3. After $t=0.5$ ps the profile of the ion density in the bulk plasma is close to that of self-similar expansion with $z=11$ and T_c, which is less than the instantaneous electron temperature as seen in Fig. 2. The same fitting for the fast ion distribution with $z=7$ gives a temperature significantly higher than $T_h=2\langle E_h\rangle/3\sim27$ keV. It implies that the velocity distribution of hot electrons is anisotropic, while the distribution of cold electrons is isotropic. Hot electrons with

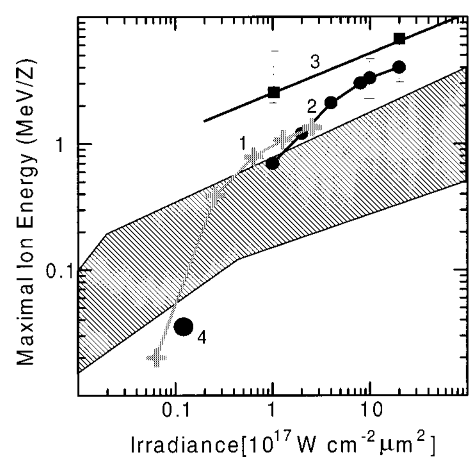

FIG. 4. Maximal energy of accelerated ions per ion charge versus the laser irradiance $I\lambda^2$. Crosses (curve 1), present calculation; circles (curve 2), [8]; squares (curve 3), [9]; the filled area represents the maximal energy of protons obtained in numerous long-pulse-laser measurements [7]. The large closed circle, energy of Xe^{+40} accelerated from laser-irradiated clusters [32].

initially anisotropic distribution in the direction normal to the plasma surface have no collision during 1 ps when their energy exceeds 40 keV ($\sim T_h$) and their quiver energy (a few keV) is much less than T_h. The ion distribution is close to that obtained by a hydrodynamics code [18] with heuristic parameters: $T_c \sim 2$ keV, $T_h/T_c \geqslant 25$, $f_h \leqslant 10\%$, and $\varepsilon_{\max} = 6T_h$. We also find a highly anisotropic spectrum of ions. This strong directedness of ions, $\theta \sim O(10^{-3})$, is due to the strong anisotropy of hot electrons. This is significant, as the emitted ions form an ion beam with exceptionally low emittance.

The dependence of maximal ion energy on laser intensity is presented in Fig. 4 for the backward acceleration, showing a nonlinearity as $E_{\max} \sim T_h \sim I^{1/3-1/2}$. The energy for the forward acceleration is approximately 20% less than that for the backward acceleration at $I = 4 \times 10^{16}$ W/cm^2. At a lower intensity $I \sim 10^{15}$ W/cm^2, we observe no MeV ions, the absorption efficiency to ions is less than 10%. At intensity $I = 4 \times 10^{16}$ W/cm^2 the amount of ions accelerated over 1 MeV exceeds 1% of the total foil mass. Figure 4 also illustrates the dependence of the maximal ion energy on the laser irradiance in our calculation, showing several reference points of experiments [7–9,32]. A number of these past experimentally measured maximum ion energy follow nicely with our theory.

In conclusion we have demonstrated that the irradiation of thin metallic foils by an obliquely incident *p*-polarized, picosecond laser pulse leads to an efficient emission of multiple-charged ions ($z = 6-7$) with energy over 1 MeV even at a modest intensity $I \sim 10^{17}$ W/cm^2.

The acceleration by the expansion driven by hot electrons is enhanced in the presence of strongly anisotropic electron velocity distribution. The conversion of laser energy through electrons into ion energy with the foil irradiation is very efficient (25% and for ions over 1 MeV energy 10%). We find that in spite of the absence the radiative losses and heat transfer, this efficiency is high enough to constitute the large dissipation mechanism and very high (up to 50%) absorption of laser light. To our knowledge, this mechanism at this regime we described above provides one of the most efficient energy conversion to ions. The ionization effect plays a significant role in determining the energy of accelerated ions. We anticipate strongly anisotropic, very high flux of energetic (>1 MeV) ions emitted out both forward and backward from the irradiated foil surface.

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