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Energetic-ion generation by the combination of laser pressure and Coulomb explosion*

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A scheme of generating energetic ions by the interaction of an ultrahigh-intensity laser pulse and a thin solid foil is studied. The combination of the effects of radiation pressure and Coulomb explosion makes the ion acceleration more effective. The maximum ion velocity variation with time is predicted theoretically while the temporal evolution of the electrostatic field due to the Coulomb explosion is taken into consideration. Two-dimensional particle-in-cell simulations are done to verify the theory.

Keywords: interaction of ultrastrong laser pulses and plasmas, ion acceleration, Coulomb explosion
PACC: 5250, 5250J, 5265, 5225D

1. Introduction

Laser driven proton accelerators have attracted much attention, because energetic ion beams are particularly important for fast ignition, nuclear physics, etc.[1−5] Ion acceleration from the rear side of targets with the scheme called target normal sheath acceleration (TNSA) is at present the most important mechanism to achieve high-energy ions.[6−13] High-energy proton beams generated by interaction of intense short-pulse lasers and solid targets have been observed in experiments with maximum energy up to about 58 MeV.[14−16] Using micro-structured foils, quasi-monoenergetic proton or ion beams with an energy spread of about 20% can be produced experimentally.[17,18] Because the maximum proton energy as well as conversion efficiency from a laser pulse to the produced proton beam is dependent on the target thickness, i.e. there is an optimum target thickness for a certain laser pulse,[19] thin-foil targets have been used to generate proton beams with high energy (a maximum energy of tens of MeV) in the experiments.[14−16] However, for an ultrathin foil all electrons may be driven away from the target by an intense laser pulse, and then it turns to the case of Coulomb explosion which can usually be seen in the laser–cluster interaction.[20,21]

On the other hand, an ultrathin foil can be accelerated as a whole to a maximum energy of several GeV by an ultrastrong laser pulse found in particle-in-cell (PIC) simulations.[22,23] If we can make use of the above methods synthetically, the ion acceleration could be more effective.

In fact, ion acceleration by both TNSA and light pressure has been studied.[24−26] Here we treat the problem in a relativistic regime of varied parameters. So the model of pure Coulomb explosion can further be used to calculate ion movement. How to choose suitable parameters will be discussed later. The temporal evolution of the electrostatic field due to the Coulomb explosion is taken into consideration in this paper. The velocity of the fastest ions is directly described in an expression which has a dependence on time.

We study the regime of generating energetic ions by two subsequent stages. First, an ultra-short and ultra-intense laser pulse irradiates a thin foil. The foil gains a velocity u as a whole along the direction of laser propagation due to the light pressure on it. This velocity no longer changes after the laser pulse leaves the foil. Because the laser pulse is very short, when the laser pulse leaves the target, the foil does not move forward very much although the velocity of the foil has already been very high. In the period of laser–foil interaction, the foil has no time to expand apparently, while the light pressure also helps

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to confine the heated foil, in spite of the fact that the electrons have already been heated to a very high temperature and the thermal pressure is very large. Then, after the interaction between the laser pulse and the foil has finished, the foil begins its Coulomb explosion. The ions located on the rear surface of the foil can get further acceleration in this stage due to the charge separation field.

2. Model and simulation

Now we want to calculate the maximum velocity of the ions in a foil after they are accelerated firstly by the light pressure and then by the Coulomb explosion. To make the calculation easy, we suppose that these two accelerations are completely separate. We will discuss the effect of the overlap between these two acceleration regimes later. After the laser pulse leaves the foil, the foil has a velocity u and the electrons have been heated to nearly the velocity of light in vacuum. The Coulomb explosion is asymmetric in the laboratory reference frame. But in the moving reference frame of foil with a velocity u which is given by the light pressure, the Coulomb explosion is still quite symmetric as we will see. Under three assumptions we obtain the following results: (i) the target thickness l is much less than its transverse dimension R; (ii) all the electrons escape from the target; (iii) half of the electrons gain momentum $p_{\mathrm{e},x}$, and the rest gain momentum $-p_{\mathrm{e},x}$. It is convenient for us to consider the pure Coulomb explosion in the moving reference frame in a quasi-one-dimensional geometry. In fact, in our simulation, about half of the electrons move forward and the rest move backward on the whole in the moving reference frame. It may be that the heating mechanism here causes the random direction of the hot electrons and the electron velocity tends to a Boltzmann distribution. E. Fourkal *et al*[27] have given an expression for the electrostatic field for the pure Coulomb explosion as $\tilde{E}(\tilde{x},t) = 4\pi Z_{\mathrm{i}} e n_0 \tilde{x}/\left(1+2\pi n_0 Z_{\mathrm{i}}^2 e^2 t^2/m_{\mathrm{i}}\right)$, where $\tilde{x}$ is the coordinate in this reference frame along the direction of laser propagation, m_{i} is the ion's mass and $n_0 = n_{\mathrm{e}}/Z_{\mathrm{i}}$ is the initial density of ions where Z_{i} is the ion charge number. For an ultrahigh-intensity laser pulse, full-ionization of the target is possible, and hence we can choose Z_{i} to be equal to its atomic number in our theoretical work. Obviously, the ions located at $\tilde{x} = l/2$ experience the maximum electrostatic field

$$\tilde{E}(l/2,t) = 2\pi Z_{\mathrm{i}} e n_0 l/\left(1+2\pi n_0 Z_{\mathrm{i}}^2 e^2 t^2/m_{\mathrm{i}}\right), \quad (1)$$

and consequently they can get the maximum momentum.

Substituting Eq.(1) into the one-dimensional equation of motion of ions

$$\frac{\mathrm{d}\tilde{p}}{\mathrm{d}t} = Z_{\mathrm{i}} e \tilde{E}, \quad (2)$$

and integrating it, taking into account the relativity of the maximum momentum $\tilde{p} = \gamma m_{\mathrm{i}} \tilde{v}$, we can get the expression $\tilde{v}/\sqrt{1-\tilde{v}^2} = lZ_{\mathrm{i}} e\sqrt{2\pi n_0/m_{\mathrm{i}}}\arctan(\sqrt{2\pi n_0/m_{\mathrm{i}}} Z_{\mathrm{i}} e t)$, where $\tilde{v}$ is the maximum velocity of the ions. Dimensionless variables are used as follows: $\tilde{v} = \tilde{v}/c$, $L = l/\lambda_L$, $N = n_0/n_c = 4\pi e^2 n_0/\omega_L^2 m_{\mathrm{e}}$, $M = m_{\mathrm{i}}/m_{\mathrm{e}}$ and $T = t/(\lambda_L/c) = t/(2\pi/\omega_L)$, where λ_L and ω_L are the laser wavelength and frequency respectively, n_{c} is the plasma's critical density and m_{e} is the electron mass. Then we get the expression of the normalized maximum velocity of the ions and it varies with time

$$\tilde{v} = \pm\eta/\sqrt{1+\eta^2}, \quad (3)$$

where $\eta = 2\pi Z_{\mathrm{i}} L\sqrt{N/2M}\arctan(2\pi Z_{\mathrm{i}} T\sqrt{N/2M})$. When $t \to \infty$, the final maximum velocity of the ions is $\tilde{v}_{\max} = \pm\eta_{\max}/\sqrt{1+\eta_{\max}^2}$, where $\eta_{\max} = \pi^2 Z_{\mathrm{i}} L\sqrt{N/2M}$.

Since our interest is in the ions which are moving forward, which get the maximum velocity in the laboratory reference frame, we only take the positive sign of the velocity. Using a Lorentz transformation we get the maximum velocity at different times in the laboratory reference frame

$$v = (u+\tilde{v})/(1+u\tilde{v}), \quad (4)$$

where u is the average velocity of all ions in the foil. When $t \to \infty$, the final maximum velocity of the ions is

$$v_{\max} = (u+\tilde{v}_{\max})/(1+u\tilde{v}_{\max}). \quad (5)$$

To verify our results, here we do fully relativistic 2D3V (two dimensions in coordinates and three dimensions in velocities) PIC simulations based on the code PPICC.[28] A circularly polarized laser pulse with wavelength $\lambda_L = 1$ μm propagates along the x direction. The circularly polarized laser pulse is used so that electrons escape from the foil mainly at the end of the first stage. Otherwise, electrons are heated very quickly and escape from the foil immediately if a linearly polarized laser pulse is used. The pulse profile in time and space is $I = I_0 \exp^2(-w^2/w_0^2)\sin^2(\pi(x-ct)/l_L)$ for $0 \le x-ct \le l_L$. The pulse peak intensity

$I_0 = 1.38 \times 10^{22}$ W/cm^2 (i.e. $a_0 = 100$, the normalized vector potential), the pulse length $l_L = 10\lambda_L$ (i.e. $T_L = 10\,(\lambda_L/c)$), the focal spot radius $w_0 = 8\ \lambda_L$ and the focus is located at $x = 17\ \lambda_L$. The pulse has a sudden beginning with $a = 70$ in the ascending front, like that used in Ref.[23], in order that the thin foil will not be heated too much and confined well by the light pressure. The over-dense slice is initially 10 λ_L in width and 1 λ_L in thickness at $x = 17\ \lambda_L$. The slice is of initial uniform density $n_{\rm e} = n_0 = 20n_{\rm c}$, where $n_{\rm c}$ is the critical density. The simulation box is $80\lambda_L \times 40\lambda_L$ with grids of 1600×800 in x, y directions. The ion mass $m_{\rm i} = 1836m_{\rm e}$, where $m_{\rm e}$ is the electron mass, and the ions have the same absolute charge as electrons (i.e. the ions are protons). The boundary conditions are periodic along the y direction and absorbing along the x direction. The numbers of the ions and the electrons are both 400000 and the initial temperature is 0.3 keV, which is required for numerical reasons. Since the foil will be heated to a much higher temperature in practice and all of the electrons are pushed away from the foil, it does not affect the result in our case, as we consider a pure Coulomb explosion.

3. Discussion

In this section, firstly, we discuss the parameters that can make the scheme mentioned above work. Then, the simulation results are taken to be compared with our theory.

First, while a thin foil is easy to accelerate by radiation pressure, the foil should be thick enough so that electrons cannot be directly expelled away from the ion plasma by the Lorentz force. So it was roughly estimated as $a_0 < E_0 = \pi NL$. But in fact, the laser field inside the foil is smaller than that in vacuum. A laser pulse slightly larger than this estimate still can be used. Secondly, a long laser pulse can accelerate the foil as a whole in the first stage for a long time. However, the foil will begin to expand in the first stage due to the excess of positive charge in fact. So, to ensure the foil does not expand too much in the first stage, too long a pulse duration is not useful. As a rough estimate, the model of pure Coulomb explosion is used. So, in order to ensure the foil does not expand too much before the second stage, the laser pulse length T_L should be less than the time $t_c = \sqrt{M\,(d-L)/2NL}/\pi$ at which the thickness of the foil expands equally to the initial width d of the foil. In our case, $t_c \simeq 6.5$ and we choose $T_L = 7.7$.

The average ion momentum versus time and the corresponding acceleration versus time in the laboratory reference frame are shown in Fig.1. At $t_{\rm I} = 35T$ ($t_{\rm I} = 0$ is the beginning time of the simulation and the subscript I corresponds to the first regime), the interaction of the laser pulse with the foil is finished and the average momentum of the ions starts to be constant. At this moment the foil has gained a velocity, u, while it has not moved forward far away from its initial position. For total reflection of the laser pulse, the average ion velocity can be estimated as $u_t = (1 - (\varepsilon_{\rm i}/m_{\rm i}c^2 + 1)^{-2})^{1/2} = 0.546$ by using energy and momentum conservations, where $\varepsilon_{\rm i} = 2\chi^2\varepsilon_L^2/(2\chi N_{\rm i}\varepsilon_L + N_{\rm i}^2 m_{\rm i}c^2)$. Here, $\chi\varepsilon_L$ is the energy absorbed by the foil from the laser pulse, $N_{\rm i}$ is the number of ions in the foil and $\chi = 1$ for the total reflection condition.[23] But in our simulation the laser pulse is not totally reflected, because a part of the laser pulse is absorbed by the foil and the other part passes through besides the part which is reflected by the target. So the foil gains a smaller velocity $u = 0.4453$, which is obtained in the PIC simulation and the corresponding reflection coefficient is $\chi = 0.71$. The acceleration $\partial v/\partial t$ is normalized by c/T. We can find that the maximum acceleration is at about $23T$ and then the acceleration finishes at about $35T$ (this is shown in Fig.1).

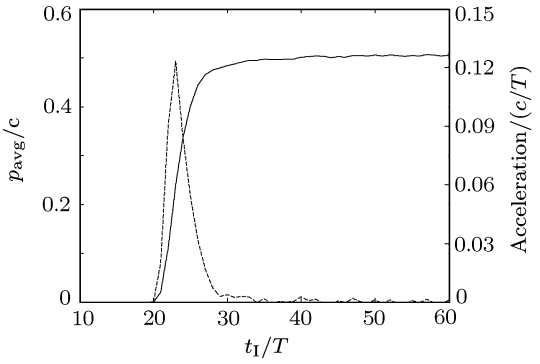


Fig.1. Average ion momentum versus time (solid line) and corresponding acceleration versus time (dashed line) in the laboratory reference frame. The acceleration is the ratio of $\partial v/\partial t$, so its unit is normalized by c/T. All quantities are normalized.

In the first stage of acceleration the foil is accelerated macroscopically by the radiation pressure as a whole. But in fact these ions are not accelerated in the same constant field. The laser field decays inside the foil due to the over-dense plasma, so that the charge seperation field has a longitudinal sturcture. The ions accelerated in this moving electrostatic field are microscopically accelerated by electrostatic shock in the

moving frame as described in Ref.[29]. Figure 2 shows the phase space plots of the foil for longitudinal ion velocities at $t_{\rm I} = 25T$ in the moving reference frame. It can be seen from the figure that there is an electrostatic shock acceleration.[29] According to Ref.[29], the maximum velocity of the shock front is

$$v_s = \left(-\frac{a^2}{NM} + \sqrt{\left(\frac{a^2}{NM}\right)^2 + \frac{4a^2}{NM}} \right) \Big/ 2 = 0.401$$

and correspondingly the maximum velocity of ions is $v_{\rm i} = 2v_s/(1+v_s^2) = 0.691$. It is shown in Fig.1 that the acceleration finishes at $35T$, so the maximum velocity in the laboratory reference frame at $35T$ is the maximum velocity which the ions can gain in the first stage. At this moment the maximum velocity in the laboratory reference frame is 0.6587 in the simulation, which is slightly smaller than the maximum ion velocity predicted by shock theory. This is because the laser pulse in Ref.[29] is a plane wave, while in our simulation it is a Gaussian wave in transverse and the amplitude $a = 100$ used above in the calculation is not the average amplitude but the peak amplitude.

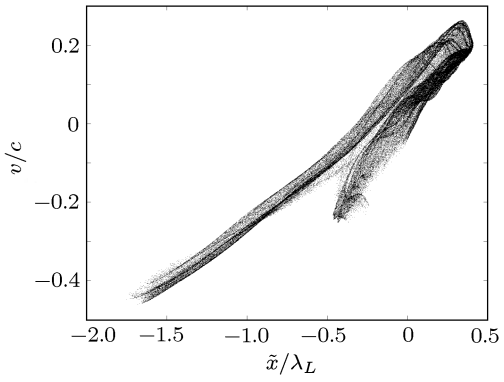


Fig.2. Ion phase space plot of the foil with longitudinal velocity at $t_{\rm I} = 25T$ in the moving reference frame. $\tilde{x}$ is the coordinate in the moving reference frame in the same direction of x. All quantities are normalized.

From $t_{\rm I} = 35T$ (viz. $t_{\rm II} = 0$, the subscript II corresponds to the second acceleration regime), Coulomb explosion begins to be dominant. In this stage, due to the conservation of momentum, only the distribution of momentum changes with the Coulomb explosion. The plots of peak electrostatic fields versus time are shown in Fig.3, asterisks standing for the simulation results and the solid line for the theoretical results. The electrostatic field decreases considerably within about ten laser periods, so the ion acceleration due to Coulomb explosion takes place mainly in this period.

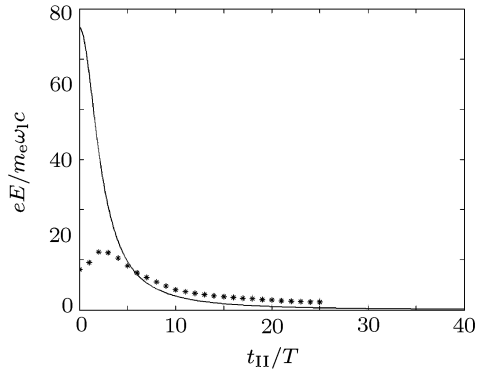


Fig.3. Electrostatic field peak versus time; asterisks stand for the simulation results and the solid line for the theoretical result. All quantities are normalized.

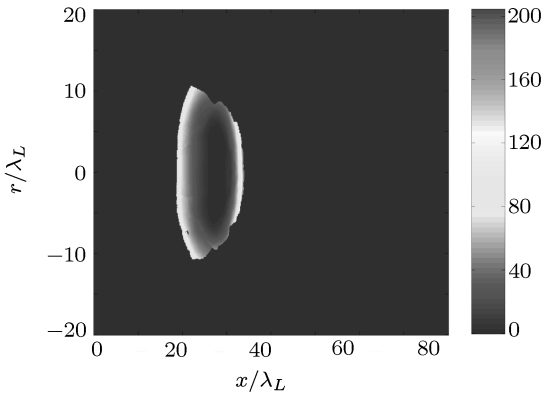


Fig.4. Ion energy plot at $t_{\rm II} = 10T$ in the moving reference frame. Only ions with velocities above zero in the laboratory reference frame are accounted for. The energy unit is MeV. All quantities are normalized.

The ion energies at $t_{\rm II} = 10T$ in the moving reference frame are shown in Fig.4. A small amount of ions, whose velocities are below zero in the laboratory reference frame, are dropped so that the part we are concerned about in this article is clearer. As we can see, the explosion is basically symmetric, which matches our assumption that the Coulomb explosion is symmetric in the moving reference. Although the 3D effect becomes important later, up to $t_{\rm II} = 10T$, we can also find in Fig.4 that the explosion is basically one-dimensional (1D). So, the 1D theory works well, especially for ions in the middle in transverse. Some time later, the thickness of the foil becomes larger and larger and the effect of the three-dimensional (3D) Coulomb explosion comes into play. However, as soon as the 3D Coulomb explosion works, the ion acceleration efficiency will drop immediately in comparison with the 1D Coulomb explosion.

Figure 5 shows the maximum ion momentum p predicted theoretically (solid line) and the results from the simulation (asterisk) at different times in the laboratory frame. The simulation results do not match very well in the early part of the second stage as explained below. Because the two acceleration regimes overlap in our simulation, the separation of the two stages is not very clear as we assumed. The ions have already begun to expand in the moving reference frame before the second stage starts. Therefore the deflection between the simulation and the theoretical ones is very large when $t_{\rm II} < 3T$. Because the maximum velocity due to the Coulomb explosion is determined by the initial condition that the ions have an undisturbed ion density distribution, the influence of when and how the electrons move out of the ion layer at the end of first stage and the beginning of the second stage wears away as time goes by. Consequently the simulation results match the theory better after $t_{\rm II} = 3T$. At $t_{\rm II}= 25T$, the later part of the second acceleration stage, the maximum ion kinetic energy is $\varepsilon_{\rm i} = 742.6$ MeV. Compared with the energy ($\varepsilon_{\rm i} = 302.1$ MeV) at $t_{\rm I}= 35T$, at the end of the first acceleration stage, we find that the maximum ion kinetic energy has increased about 440 MeV. So in the second regime, the ion kinetic energy can be increased further on the basis of the first regime and both regimes are important for ion acceleration. For a certain laser pulse, the foil parameters decide which regime is more dominant. If the foil is very heavy, i.e. the foil density is very high or the foil is very thick, the acceleration of the laser pressure is relatively weak for such a foil while the Coulomb explosion is impetuous. If the foil is very light, the acceleration of laser pressure is dominant while the Coulomb explosion is relatively mild.

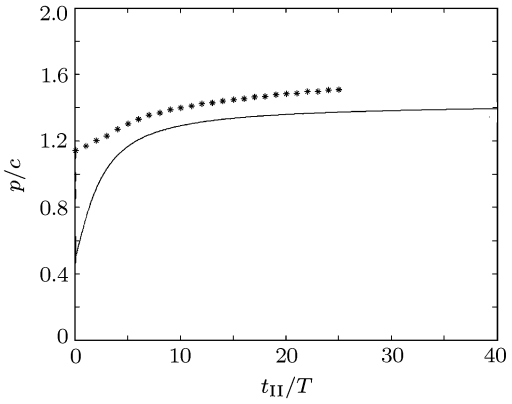


Fig.5. The maximum momentum predicted theoretically (solid line) and the results from the simulation (asterisk) at different times. The average velocity of all ions in the foil is $u = 0.422$. All quantities are normalized.

4. Conclusion

In this paper we studied the interaction of an ultrahigh-intensity laser pulse and a thin solid foil. The intensity of the laser pulse is so high and the foil is so thin that the effect of laser pressure and Coulomb explosion can be used to accelerate the ions subsequently. We treat the problem in the relativistic regime under two stages. In the first stage, the details of acceleration can be explained well by the theory of shock acceleration. In the second stage the ions are further accelerated by the electrostatic field due to the Coulomb explosion. We take the temporal evolution of the electrostatic field into consideration and the maximum longitudinal velocity predicted in a quasi-one-dimensional geometry matches the simulation quite well. The acceleration can be more efficient if optimal parameters of the laser pulse and foil are chosen (not done in this article) so that the ions experience sufficient acceleration at each stage.

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