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On the maximum energy of ions in a disintegrating ultrathin foil irradiated by a high-power ultrashort laser pulse

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***Abstract*.** **The theory of Coulomb explosion of a plasma is used to estimate the maximum energy of ions produced upon irradiation of an ultrathin foil by a relativistically strong ultrashort laser pulse.**

Keywords: *plasma, ultrathin foil, ultrashort laser pulse.*

Due to the growing interest towards practical applications of high-energy ion fluxes accelerated upon irradiation of various targets by short laser pulses, designs of such accelerating devices based on the use of various targets as well as laser pulses with different parameters are being discussed actively at present. The advances in the technology of producing high-quality ultrathin plane targets (foils of thickness 100 – 1000 Å) and relativistically strong ultrashort laser pulses (whose duration is only an order of magnitude longer than the laser-field period) with a high intensity contrast preventing the destruction of the target by the prepulse have opened the prospects of conducting experiments on fast-ion generation.

A strong laser field can knock out all electrons from a thin target thus creating conditions for a subsequent Coulomb explosion of the positively charged plasma layer. Such a process is identical to the one occurring in clusters [1 – 5], and if the focal-spot size is much larger than the target thickness, it can be simulated as the solution to the Cauchy problem for the Vlasov – Poisson equations describing an exploding plane charged plasma layer in one-dimensional geometry. With the passage of time, as the plasma spreads over the distance comparable to the focal-spot size, the propagation of ions becomes three-dimensional. In this case, the natural question arises how to estimate the maximum energy eventually acquired by the ions. This paper is devoted to solution of this problem and analysis of the conditions under which such a regime of ion acceleration can be realised.

We begin with the solution of the initial one-dimensional problem for the nonrelativistic Vlasov ion equation (or, in the cold particle approximation, the equivalent hydrodynamic equations) with a self-consistent electric field satisfying the Poisson equation. The initial ($t = 0$) ion density profile $n_0(x)$ is assumed to be given as symmetric (relative to $x = 0$) and descending (for $|x| \to \infty$) with a characteristic half-width l. Initially, the ions are assumed to be at rest. From this solution, we obtain the distributions for the ion density $n(x, t)$ and the average ion velocity $v(x, t)$ presented in the parametric form through the spatial variable h:

$$x = h + \frac{t^2 w(h)}{2}, \quad w(h) = \frac{4\pi Z^2 e^2}{M}\int_0^h n_0(y)\mathrm{d}y,$$
$$v(t, x) = tw(h), \quad n(t, x) = n_0(h)\left(1 + \frac{t^2\omega_{\mathrm{pi}}^2}{2}\right)^{-1}, \quad |h| \leqslant l, \tag{1}$$

where $Ze \equiv e_{\mathrm{i}}$ and M are the ion charge and mass, respectively, $w = e_{\mathrm{i}}E/M$; and ω_{pi} is the Langmuir ion frequency calculated from the initial density $n_0(0)$ at the centre of the foil for $x = 0$.

Solution (1) is illustrated in Fig. 1 by the spatial distributions of the density and velocity of ions for $\omega_{\mathrm{pi}}t = 2$ and 4 for two initial density distributions $n_0(x)$ in the plasma layer: stepwise distribution (homogeneous foil) and Gaussian distribution $n_0(x) = (2/\sqrt{\pi}) \times \exp(-x^2/l^2)$, for the same total number of particles in the foil. A comparison of curves in Fig. 1 shows that the homogeneous foil model is qualitatively applicable for the foil boundary smoothing over a distance of the order of, or smaller than, half its thickness. Note that, unlike the cylindrical or spherical expansion of a plasma [4, 5], no overturning of the Coulomb explosion wave occurs in the case of a disintegrating plane layer. In other words, the hydrodynamic approach is sufficient for describing the expansion of a plane foil (in contrast to the non-one-dimensional case) [6]. In real experiments, however, one-dimensional expansion of thin films exposed to short laser pulses is replaced eventually by three-dimensional expansion. This happens when the plasma expands at a distance approximately equal to the size d of the focal spot of laser radiation. For $d \gg 2l$, the ion velocity in an exploding homogeneous foil achieves the value

$$v_{\max}^{(1\mathrm{D})} = \omega_{\mathrm{pi}}\sqrt{ld}. \tag{2}$$

Subsequent expansion of the plasma is three-dimensional, and it is natural to consider the extent to which the ion energy increases at this stage compared to the value

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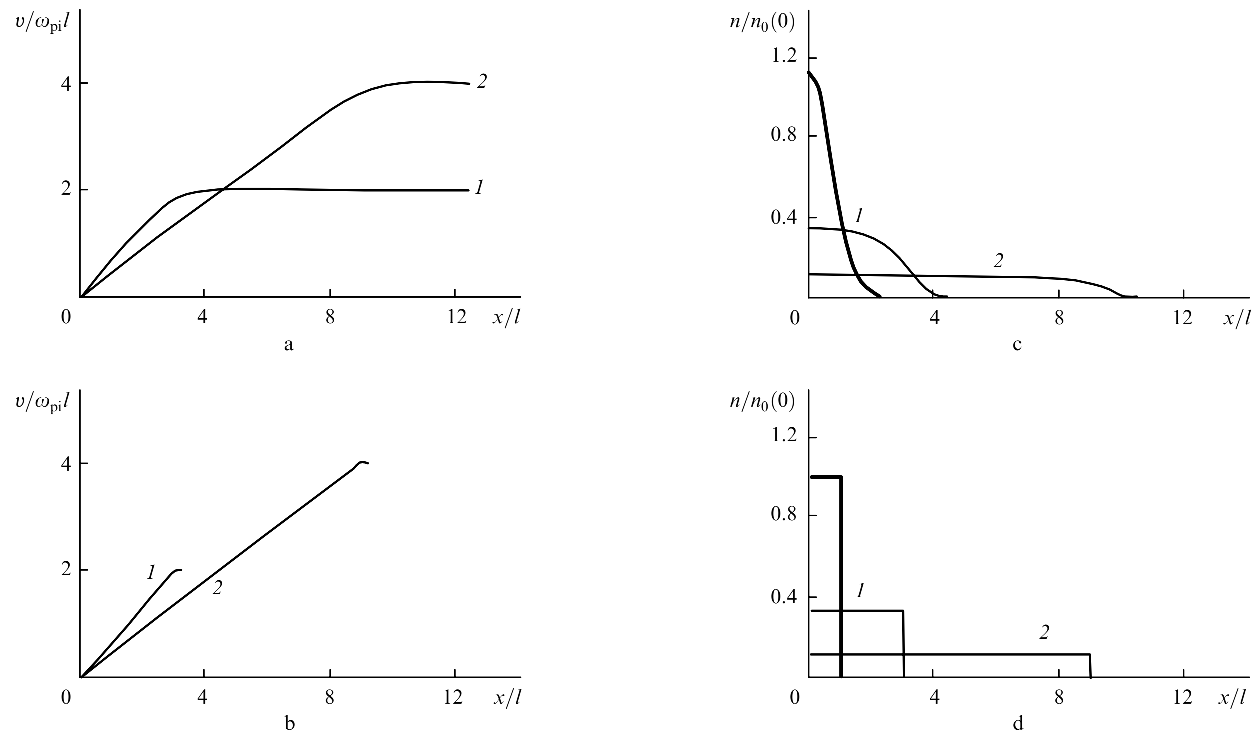

Figure 1. Spatial distributions of the velocity (a, b) and density (c, d) of ions at $\omega_{\rm pi}t = 2$ [curve (*1*)] and 4 [curve (*2*)] for two initial density distributions in the foils: Gaussian distribution $n_0(x) = (2/\sqrt{\pi})\exp(-x^2/l^2)$ (a, c) and step distribution (b, d) for the same total number of particles in the foil. Bold curves in Figs c and d show the initial density profiles.

achieved in the one-dimensional case, i.e., $Mld\omega_{\rm pi}^2/2$ [see Eqn (2)].

We perform the estimate by using the theory of spherical expansion of a charged plasma bunch [5]. Unlike the case in [5], we take for the initial conditions the distributions of density, average velocity and electric field corresponding to the one-dimensional solution (1) at the instant $t = t^*$ when the ideal foil expands over a distance $d/2$. For cold collisionless hydrodynamics equations and the Poisson equation describing the spherical expansion of a homogeneous ion bunch the corresponding initial conditions are

$$n = \frac{n_0(0)}{1 + \omega_{\rm pi}^2 t^{*2}/2}\,\theta(1 - 2r/d)\,, \quad \upsilon = \frac{t^* r\omega_{\rm pi}^2}{1 + \omega_{\rm pi}^2 t^{*2}/2},$$

$$E = \frac{(M/e_{\rm i})r\omega_{\rm pi}^2}{1 + \omega_{\rm pi}^2 t^{*2}/2}. \tag{3}$$

Here, θ is the step function. The solution of this problem can be written in parametric form in terms of the variables q and g:

$$\sqrt{\frac{2}{3}}\tau\mu\left[1 + \frac{3}{2}(\mu t^*)^2\right]^{3/2}$$
$$= \frac{1}{2}\ln\frac{\left[1 + (3/2)(\mu t^*)^2\right]^{1/2} + \left[q^2 + (3/2)(\mu t^*)^2\right]^{1/2}}{\left[1 + (3/2)(\mu t^*)^2\right]^{1/2} - \left[q^2 + (3/2)(\mu t^*)^2\right]^{1/2}}$$
$$+ \frac{1}{2}\ln\frac{\left[1 + (3/2)(\mu t^*)^2\right]^{1/2} - (3/2)^{1/2}\mu t^*}{\left[1 + (3/2)(\mu t^*)^2\right]^{1/2} + (3/2)^{1/2}\mu t^*}$$
$$+ \frac{\left[1 + (3/2)(\mu t^*)^2\right]^{1/2}}{1 - q^2}$$
$$\times\left\{\left[q^2 + (3/2)(\mu t^*)^2\right]^{1/2} - (1 - q^2)(3/2)^{1/2}\mu t^*\right\},$$
$$\upsilon(t, r) = \sqrt{\frac{2}{3}}\mu g\left[q^2 + (3/2)(\mu t^*)^2\right]^{1/2}, \quad r = \frac{g}{1 - q^2},$$
$$\tau = t - t^*, \quad g \leqslant \frac{d}{2}, \tag{4}$$

where $\mu^2 = \omega_{\rm pi}^2/(1 + \omega_{\rm pi}^2 t^{*2}/2)$. It follows from these expressions that the maximum ion velocity achieved at the boundary of the expanding bunch for $\tau \to \infty$ (this corresponds to $q \to 1$) can be presented in the form

$$\upsilon_{\max}^{(3{\rm D})} = \omega_{\rm pi}\left(\frac{4ld}{3}\right)^{1/2}, \tag{5}$$

which determines the maximum energy $\epsilon_{\max} = 2Mld\omega_{\rm pi}^2/3$ of the accelerated ions.

Thus, we conclude that the ions acquire their energy mainly in the one-dimensional regime of the Coulomb explosion of the foil. A comparison of Eqns (2) and (5) shows that at the stage of three-dimensional expansion of the foil, the energy acquired by the ions is just one-fourth of the maximum energy. The maximum energy of the ions is directly proportional to the thickness of the foil, its density, and the size of the focal spot of the laser. In the real experiment, the energy acquired by the ions may not attain the value $\epsilon_{\max} \approx Mld\omega_{\rm pi}^2$ due to a possible reverse radial current of cold electrons, which compensates the charge in the focal region. The efficiency of such a compensation can be estimated by taking into account the collisions and the corresponding nonlocal transport processes. For this reason, $\epsilon_{\max}$ may be treated as the limiting energy of ions accelerated from thin foils under the action of strong laser pulses.

In order to estimate the required intensity of laser radiation, we consider the Coulomb energy (per unit area) $\mathcal{E}_c \approx 2\pi e_i^2 n^2 l^2 d$ stored in the charged plasma. The corresponding energy $\mathcal{E}_e \approx n_e l m c^2 a^2$ acquired by the electrons in the relativistically strong laser field must be considerably higher than $\mathcal{E}_c$. Here, e is the electron charge; n_e is the density of electrons ($en_e = e_i n = Zen_i$); m is the electron mass; $a = eE_{las}/m\omega c$ is the dimensionless amplitude of the laser field E_{las}; ω is its frequency; and c is the velocity of light.

Thus, the Coulomb explosion regime is realised for $a^2 > \omega_{pe}^2 ld/c^2$, where ω_{pe} is the plasma frequency of electrons. This means that, for a relativistically strong laser pulse penetrating the dense plasma, the skin layer ac/ω_{pe} exceeds the geometrical mean of l and d. Keeping in mind the above inequality, we arrive at the following constraint on the value of the limiting ion energy: $\epsilon_{max} < Zmc^2 a^2 = 0.5Za^2$ MeV. For modern laser devices like the one considered in [7], we have $a > 100$, which indicates that ions of energy ~ 1 GeV can be obtained by exposing thin foils to optical pulses with a high-intensity contrast.

Our analysis of the efficiency of ion generation upon the Coulomb explosion of plane targets shows that exposure of foils of submicron thickness to ultrashort laser pulses with a high contrast may serve as an effective means of obtaining ions of energy ~ 1 GeV. Since the required laser beam intensity has already been attained, the main progress should be expected in the direction of improving the contrast of laser radiation.

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