The number of fast ions in a laser plasma

V. P. Silin

P. N. Lebedev Physics Institute, USSR Academy of Sciences
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It is demonstrated that the number of high-energy ions produced when a powerful laser beam acts on a target can be determined if one assumes a rapid establishment of the electromagnetic field in the plasma and a rapid density-profile deformation due to the plasma acceleration in a small region with growing field.

When a spherical target is isotropically compressed by radiation, part of the light flux can be p-polarized, i.e., the electric-field vector of the laser radiation has a component normal to the target surface. Under these conditions, an increase of the electric field takes place in the plasma corona in the region of plasma density close to critical ($r \approx r_0$), where the Langmuir frequency becomes comparable with the laser frequency.[1,2] Since the increase of the field is localized in the case of p-polarized light in a small region, outside of which it decreases rapidly, the action of such a field can be regarded, within the framework of the motion of plasma acceleration by an electromagnetic wave to which the plasma itself is opaque.[3] As shown in[3], under conditions when the field momentum flux greatly exceeds the thermal pressure, the plasma acquires a velocity V given by

$$\frac{E^2}{4\pi} = V^2 \Sigma n_i M . \tag{1}$$

Here E is the electric field intensity, n_i is the density of the number of ions at the critical point, M is the ion mass, and the summation is over the species of ions.

That accelerated ions are produced in the presence of p-polarization was established experimentally in[4], with microwaves applied to a plasma. This effect was also revealed in a numerical experiment.[5] Fast ions in a laser plasma were reported in[6,7].

In accord with the premises of[3], when the electromagnetic field accelerates the plasma it acts on it like an infinitely heavy wall that moves with velocity V. It is obvious that the energies of ions of different species are proportional in this case to their masses.

An important feature of the phenomenon discussed by us is the dependence of the velocity of this motion on the coordinate, this being due to the decrease of the electric field intensity with increasing distance from the critical-density point r_0. When the electric field decreases sufficiently to make the velocity $V(r)$ comparable with the speed of sound v_s, the ion-acceleration efficiency decreases. It can therefore be stated that accelerated ions are produced with velocities ranging from that of sound to a value $V_{\max}$ determined by the maximum field value. At the same time we can estimate the total number of ions that take part in the acceleration, since we can estimate that spatial region in which the velocity of the electromagnetic wall lies in the range from $V_{\max}$ to v_s.

To estimate the energy of the accelerated ions and their number we can use the results of the linear theory of the electromagnetic field near the critical point, bearing in mind that the plasma-particle acceleration considered by us is a relatively slow process constituting a nonlinear restructuring of the plasma under the influence of the rapidly produced field, which does not produce initially a nonlinear change in the plasma density if no account is taken of the slow displacement of the ions. Then, according to[1,2], the normal component of the electric vector near the point r_0 can be represented in the form

$$|E_r| = \frac{\phi E_0}{\sqrt{2\pi\rho}} \left\{ \left(\frac{r - r_0}{a} \right)^2 + \frac{\nu^2}{\omega_0^2} \right\}^{-1/2} \tag{2}$$

Here a is the characteristic distance over which the plasma density changes ($n = n_0[1 - (r - r_0)/a]$), ν is the effective electron-collision frequency, the exponent of the rate at which the field is turned on or $\omega_0^{1/3}(v_{Te}/a)^{2/3}$, ω_0 is the radiation frequency, E_0 is the amplitude of the electric field in the light beam, $\rho = a\omega_0/c$, and ϕ is a function of the angle of incidence of the light and reaches a value ~1.2 at the maximum.

It is obvious that according to formulas (1) and (2) the maximum ion velocity is

$$V_{max} \approx \frac{E_0 \phi}{\sqrt{4\pi n_i M}} \sqrt{\frac{c\omega_0}{2\pi a}} \frac{1}{\nu} . \tag{3}$$

The region in which $V > v_s$ has a width

$$\Delta r \sim a \frac{\phi}{\sqrt{2\pi\rho}} \left[\frac{E_0^2}{4\pi(n_e \kappa T_e + n_i \kappa T_i)} \right]^{1/2}$$

Therefore the total number of accelerated ions with velocities from v_s to $V_{\max}$ is given by

$$\delta n_i \sim n_i \frac{4\pi r_0^2 a \phi}{\sqrt{2\pi\rho}} \left[\frac{E_0^2}{4\pi(n_e \kappa T_e + n_i \kappa T_i} \right]^{1/2} . \tag{4}$$

The time during which this number of accelerated ions is produced is of the order of $\Delta r/v_1$, which is relatively quite small.

The total energy of the maximally accelerated ions is of the order of $MV_{\max}^2$ multiplied by the number of ions in the region of the field maximum, i.e., by the quantity

$$4\pi r_0^2 (a\nu/\omega_0) n_i , \tag{5}$$

which is approximately equal to the radiation energy incident on the target during the time $1/\nu$. We note that at sufficiently high radiation-energy flux density q the departure of the ions from the field-maximum region can become a rapid process. Then the maximum ion velocity can apparently be determined, not by formula (3), but by the formula $V_{\max} \sim (q/n_i M)^{1/3}$. The foregoing estimates give us an idea of the maximum values determined by the maximum value of the function ϕ.[1,2] It must be noted at the same time that the effective value of this quantity is determined to a certain degree by the structure of the laser field focused on the target. We note that the critical region becomes filled with expanding plasma, after the initial departure of the ions with velocities from V_{max} to v_s, under conditions when, first, the gasdynamic plasma pressure is comparable with the force applied by the field and, second, a local distortion of the plasma profile is produced and brings effectively closer together the points of reflection and amplification of the electromagnetic wave. The subsequent filling of the critical region by the expanding plasma can therefore lead to the appearance of ions with velocities V_{max} only if the light beam contains waves with large incidence angles.

For neodymium-laser radiation with energy flux density $q \sim 10^{14}$ W/cm^2 and a plasma temperature $T \sim 1$ keV. The energy of the maximally accelerated ions can amount to dozens of keV. At a target radius ~0.1 cm, the number of such ions can reach according to (5) a value 10^{11}. At the same time the total number of accelerated ions is $\sim 3 \times 10^{15}$ or a fraction of one percent of the total 10^{18} ions in the corona (assuming that characteristic homogeneity scale is of the order of the dimensions of the focal spot, 10^{-2} cm). The time of this acceleration is $\sim 10^{-11}$ sec.

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