Observation of fast ions in a laser plasma

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(Submitted March 18, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 9, 415–418 (5 May 1977)

Experiments on heating of spherical targets wth the high-power "Kal'mar" laser installation revealed a group of fast ions with energy $\lesssim 0.5$ MeV. The possible generation mechanisms are discussed.

PACS numbers: 52.50.Jm, 52.25.Lp

The appearance of a group of fast ions that carry away an appreciable fraction of the energy absorbed by the plasma has been reported repeatedly in recent years.[1] These ions were registered with the aid of time-of-flight corpuscular methods having a small angular aperture and in which the plasma is investigated during the later stages of the dispersal.

In our experiment, using high-speed multiframe interferometry,[2] we observed generation of fast ions in a plasma produced with the 9-channel laser setup "Kal'mar" and by irradiating solid and hollow targets of glass (SiO_2) of ~ 100 μ diameter. At a light-beam diameter ~ 150 μ in the target region and at an energy $E_L \approx 150$ J, the flux density was $q \sim 10^{14}$ W/cm^2.[3]

Figure 1 shows interference patterns that are typical of the experiments, when the pressure of the residual gas (H_2 or D_2) in the vacuum chamber ex-

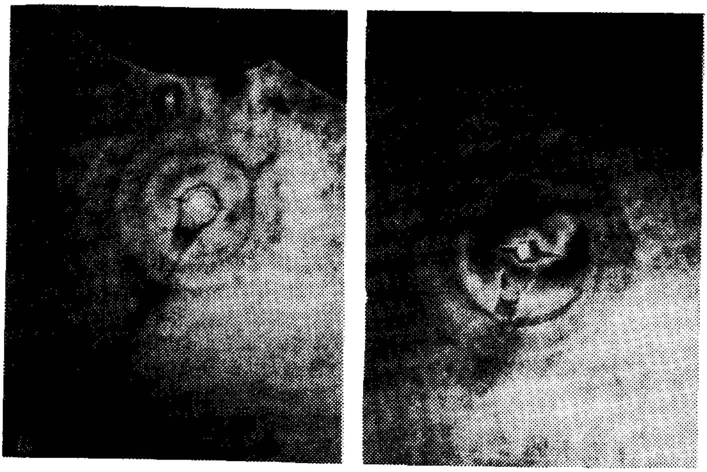

FIG. 1. Laser-plasma interference patterns. Exposure instants 3 nsec (a) and 5.5 nsec (b).

ceeded 5 Torr. Besides the spherical expansion of the plasma, one can clearly see the appearance of "jets" evidencing narrowly directed motion of a certain number of plasma particles.$^{1)}$ It follows from a reduction of the interference patterns that the electron density N_e inside the "jets" corresponds to a total ionization of the residual gas. The lower limits of the sensitivity of the employed procedure amounted to $N_eL \sim 5\times10^{16}$ cm^{-2}, which yields at $L\sim1$ mm (the characteristic dimension of the "jet") a value $N_{e,\min}\sim5\times10^{17}$ cm^{-3}. This explains the absence of "jets" on the interference patterns at pressures $p\lesssim5$ Torr.

The velocity of the directional motion of the fast plasma particles, which ionized the gas surrounding the particles, was determined from the velocity of the "jet" from the surface of the target and amounted to $\bar{v}\sim(1-2.2)\times10^8$ cm/sec. For ions with an average atomic weight $A=20$, this corresponds to an energy $E_i \gtrsim 500$ keV. The energy of electrons having such velocities is $E_e \gtrsim 15$ eV.

The energy lost by the ion as it is slowed down in the residual gas of density $\rho\sim2\times10^{-3}$ mg/cm^3 surrounding the target amounts, according to,[4] to $dE/dx \sim 20$ keV/cm. This energy is transferred to a cylindrical shock wave. Estimating the energy W of the latter from its radius,[5] namely $R\sim(W/\rho)^{1/4}t^{1/2}$, we obtain a value $W\sim0.05$ J/cm, while the number N of the fast ions in the jet is $N\sim X/(dE/dx)\sim2\times10^{13}$ or $\gtrsim1\%$ of the total number of ions in the target. The fraction of the energy carried away by the fast ions in the jet is ~5—10% of the absorbed laser energy. We note that this an upper-bound estimate, since we assume that all the jet ions have an energy $E_i\sim500$ keV.

A possible cause of formation of fast ions in the laser plasma can be "superheating" as a result of the change in the electronic thermal conductivity, for example as a result of generation of spontaneous magnetic fields.[6] In the case of irradiation of flat targets, these fields reach values $B\sim10^6$ G and possibly cause the jet-like dispersal of the plasma[7,8] under conditions when the target is not uniformly irradiated. However, in the case of a uniform irradiation of spherical targets (in our experiment this was monitored with pinpoint-camera photographs[3]) the generation of magnetic fields of high intensity is less probable.

It appears that the cause of the ion acceleration is the strong resonant electric field produced in the plasma region with critical electron density under oblique incidence of a p-polarized light wave.[9] Under the conditions of our experiment, the normal component of the field increases by several dozen times and exceeds 10^9 V/cm. This field accelerates the electrons perpendicular to the plasma surface, and the latter in turn drag with them the heavy ions.[10,11]

Obviously, in the case when the target diameter is somewhat smaller than the beam diameter, the angle of incidence of the radiation in each beam ranges from 0° (normal beam) to 90° (tangential). The resonant field E_r has then a sharp maximum near the angle θ_m determined from the condition $(k_0a)^{2/3}\sin^2\theta_m \approx (1/2)^{2/3}$.[12] Substituting the characteristic values for $\theta_m \approx 15$–$30°$, we obtain an estimate of the characteristic dimension of the variation of the electron density of the plasma, $a \sim (1-5)\times10^{-4}$ cm. We note that the last estimate is meaningful only when the region with critical density has a strictly spherical surface, since the incidence angle is assumed to be the angle between the normal to the surface and the laser beam.

Starting from the assumed ion-acceleration model, let us estimate the average critical energy of the electrons in the resonant electric field[13]:

$$< \epsilon > \approx \frac{\phi E_0 e}{2}\sqrt{\frac{a}{k_0}} \approx 4\cdot10^{-3}\,\phi\,\sqrt{qa\lambda_0}\ [\mathrm{KeV}],$$

where q is in W/cm^2, $\lambda_0 = 2\pi/k_0$ and a are in cm, e is the electron charge, E_0 is the amplitude of the electric field of the light wave in vacuum, and ϕ is a function of the incidence angle, which at the maximum is approximately equal to unity. Substituting the values $q \simeq 10^{14}$ W/cm^2 and $a \sim 5\times10^{-4}$ cm, we obtain $\langle\epsilon\rangle \sim 10$ keV. Ions with charge $\bar{z} \approx 10$ can be accelerated to average energies ~ 100 keV, but this is much lower than the energies observed in experiment.

In conclusion, the authors thank V. T. Tikhonchuk for useful discusssions.

[1)] The appearance of "jets" cannot be attributed to optical breakdown of the gas, since their direction did not coincide with any of the heating beams and varied from experiment to experiment. The angle with the nearest beam was $\theta \sim 15$–$30°$.

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