Stimulated scattering of laser radiation in a plasma

E. A. Burunov, G. M. Malyshev, G. T. Razdobarin, V. V. Semenov, and I. P. Folomkin

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences, Leningrad
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Laser radiation was found to be scattered more strongly in a plasma than by thermal fluctuations. An increase in the scattering signal was observed when the threshold condition for the excitation of a parametric instability in a plasma by electromagnetic radiation was satisfied.

Our experimental study of the scattering of laser radiation in a plasma revealed a considerable increase in the power of the scattered radiation corresponding to the ion component of the spectrum, compared with the level of scattering by thermal fluctuations. The scattering experiments were carried out using a ruby laser of 30 MW output power, whose beam was focused into a plasma in a 0.3 mm diameter spot. The wave vectors of the incident and scattered radiation were mutually perpendicular. The radiation was scattered by a plasma of a laser-generated spark during later stages, ranging from microseconds to tens of microseconds after breakdown. The scattering was collective ($\alpha = 1/kr_D > 1$). The power scattered by thermal fluctuations was calculated for the ion component of the spectrum using the known values of the concentration and temperature and applying Eq. (1) (a signal representing the plasma-scattered radiation was measured relative to a signal of the Rayleigh scattering in a gas):

$$\frac{I_p}{I_R}=\frac{n_e}{n_0}\frac{\sigma_p}{\sigma_R}, \tag{1}$$

where n_e is the electron concentration; n_0 is the number of gas molecules per unit volume; σ_R is the Rayleigh scattering cross section of a gas; σ_p is the scattering cross section of a plasma for the ion component of the spectrum.

The scattering cross section σ_p was found from the formula

$$\sigma_p=\sigma_T\frac{\alpha^4}{(1+\alpha^2)(1+2\alpha^2)}, \tag{2}$$

where σ_T is the Thomson scattering cross section and $\alpha = 1/kr_D$ (k is the length of the difference wave vector, defined as the geometric difference between the wave vectors of the incident and scattered radiation, and r_D is the Debye radius of electrons, which depends on the concentration and temperature).

The electron concentration and temperature in the spark plasma were deduced from the collective scattering spectra.

Figure 1 shows a sequence of the collective scattering spectra of a laser-spark plasma at four moments ranging from 3.6 μsec (uppermost curve) to 30 μsec (lowest curve) after breakdown. The spectra consist of a central ion peak and two electron satellites, separated by a distance decreasing with time.

The electron concentration was determined by comparing the measured frequency shift of the electron satellites in the scattered-radiation spectrum with the electron plasma frequency. Allowance was made for the temperature correction due to the dispersion relationship governing plasma waves. The plasma temperature was found from the width of the ion peak profile, obtained as a result of interferometric measurements with a Fabry-Perot etalon.

The time dependences of the electron concentration and temperature are plotted in Fig. 2. These dependences were used to calculate the signal due to the scattering by thermal fluctuations and to plot the time dependence of this signal (curve 1 in Fig. 3). The error in the determination of the signal represented by curve 1 was less than 10%. The only exception was the scattered-radiation signal corresponding to 30 μsec. The value of the signal calculated for this moment, relative to the signal due to scattering in air, was within the range 0.07–0.16. The large error (about 40%) in the determination of the amplitude of the scattered-radiation signal was due to lack of the value of the corresponding electron temperature at t = 30 μsec.[1)]

Curve 2 in Fig. 3 gives the values of the scattered-radiation signal for the ion peak found experimentally in[1] and in earlier studies.[2,3] It is clear from Fig. 3 that the measured signal was in agreement with the signal due to scattering by thermal fluctuations only during the first 10 μsec. In the case of scattering by thermal fluctuations in the absence of plasma perturbation by a laser beam, the scattering cross section should be independent of the pump wave power. Measurements were carried out using laser power reduced by a factor of 60 at a time t = 3 μsec.[2] As expected, weakening of the laser beam reduced the scattered-radiation signal in direct proportion to the laser power.

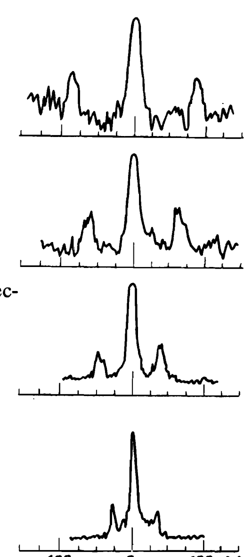

FIG. 1. Microphotograms of the collective scattering spectra.

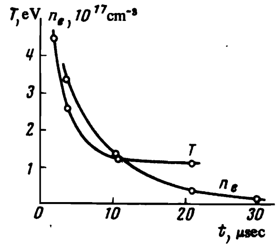

FIG. 2

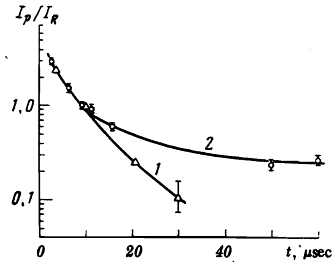

FIG. 3. Time dependences of the intensity of the scattered radiation: 1) calculated curve, representing the scattering by thermal fluctuations; 2) experimental curve.

In the time interval between 10 and 20 μsec, the scattering signals represented by curves 1 and 2 in Fig. 2 diverged. At t = 30 μsec, the experimentally determined scattering signal was over three times as high as the signal due to the scattering by thermal fluctuations. This considerable increase of the scattering signal could be due to the excitation of a parametric instability in the plasma. The threshold for the excitation of ion-acoustic oscillations in a plasma [4] corresponded to the pump wave power density such that the oscillatory and thermal velocities of electrons reached

$$\left(\frac{\tilde{v}}{v_T}\right)_{\text{th}} = 4\left[\frac{\gamma_s\tilde{\gamma}\omega_0}{\omega_s\omega_e^2}\left(1+\frac{1}{\alpha^2}\right)\right]^{1/2}, \quad (3)$$

where $v_T = (\kappa T_e/m_e)^{1/2}$ is the thermal velocity of electrons (T_e and m_e are the electron temperature and mass), $\tilde{v} = eE/m\omega_0$ is the oscillatory velocity of an electron (E and ω_0 are the intensity and frequency of the pump wave field), ω_s and γ_s are the frequency and damping decrement of ion-acoustic waves, ω_e is the electron Langmuir frequency, $\tilde{\gamma} = \nu_{ei}\omega_e^2/2\omega_0^2$ is the damping decrement of transverse waves (ν_{ei} is the electron-ion collision frequency).

In an isothermal plasma with a strong damping of ion-acoustic waves ($\gamma_s \sim \omega_s$), the ratio $(\tilde{v}/v_T)_{th}$ represents several percent for a plasma at a temperature of about 1 eV with an electron density of 10^{16}–10^{17} cm^{-3}. Between 10 and 20 μsec, the threshold value of this velocity ratio should decrease from 0.08 to 0.045 due to the fall in the electron density. In our experiments, the power density of the ruby laser radiation was about 4×10^{10} W/cm^2, which corresponded to an oscillatory electron velocity $\tilde{v} = 2.5 \times 10^6$ cm/sec. The ratio of the oscillatory to the thermal velocity $(\tilde{v}/v_T)_{exp}$, found experimentally at different moments from the beginning of a spark discharge, is plotted in Fig. 4. As the plasma cooled, the velocity ratio increased. In the interval between 10 and 20 μsec, the experimental velocity ratio $(\tilde{v}/v_T)_{exp}$ was 0.05–0.06, in good agreement with the threshold values for the parametric interaction between laser radiation and plasma.

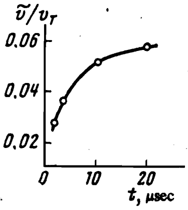

FIG. 4

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1)The range of possible temperatures at t = 30 μsec was 1.15–0.5 eV and this was the range employed in the calculation of the scattered-radiation signal and of the temperature correction to the plasma frequency (used to determine the electron configuration). The upper limit of 1.15 eV corresponded to the temperature measured during the preceding moment t = 21 μsec. The lower limit of 0.5 eV was selected with a large margin. At these very low temperatures, the degree of ionization of a plasma was very low. This was in conflict with the measured value of the electron concentration, which exceeded 10^{16} cm^{-3}.

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[2] G. M. Malyshev, G. T. Razdobarin, and V. V. Semenov, Diagn. Plazmy No. 3, 206 (1973).

[3] G. M. Malyshev, G. T. Razdobarin, and V. V. Semenov, Zh. Tekh. Fiz. **42**, 1429 (1972) [Sov. Phys.-Tech. Phys. **17**, 1137 (1973)].

[4] V. P. Silin, Parametricheskoe vozdeĭstvie izlucheniya bol'shoĭ moshchnosti na plazmu (Parametric Interaction of High-Power Radiation with Plasma), Nauka, M., 1973.

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