Parametric resonance and diagnostics of a laser plasma

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Results are presented of measurements of the spectral composition of the radiation reflected (scattered) by a plasma produced when a high-power neodymium-laser beam is focused on a flat target. It is shown on the basis of a comparative analysis of the results of the experiment and of the theory of parametric resonance in a plasma that the electron temperature in the region of the critical density can be determined from the experimentally observed red shift of the intensity of the second harmonic of the laser radiation.

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The short lifetimes and the large density and temperature gradients of a dense plasma produced by high-power laser radiation and used to solve the problem of laser control of thermonuclear fusion[1] call for the development of new methods of plasma diagnostics. In this article we call attention to the possibility of determining the electron temperature of a laser plasma, in the critical density region, on the basis of a comparative analysis of the results of experiment and the theory of parametric resonance.[2]

We investigated experimentally the spectral composition of the radiation reflected (scattered) by a plasma produced by focusing on a flat aluminum target the radiation from a nine-channel neodymium laser,[3] with energy $E \approx 200$ J in a pulse of duration $\tau \approx 2$ nsec at a flux $q \leqslant 5 \times 10^{14}$ W/cm^2. The spectra of the incident radiation and of the radiation reflected at the fundamental frequency $\omega_0 \approx 1.8 \times 10^{15}$ sec^{-1} turned out to be similar in shape, with an approximate width 50 Å at half-intensity level (Figs. 1a and b). No broadening of the spectrum of the reflected radiation or a noticeable shift of this spectrum was observed, in contrast, for example, to the results of[4]. The reflection coefficient R in the solid angle of the focusing system, just as at lower flux densities,[5] was small ($R < 1\%$). An investigation of the spectrum of the second harmonic radiated by the plasma into the aperture of the focusing system has

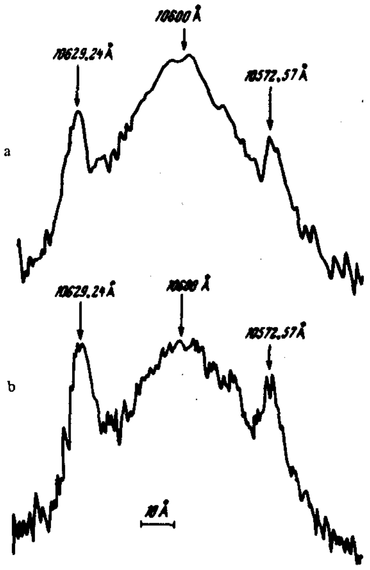

FIG. 1. Typical spectrograms of the incident radiation (a) and of the radiation reflected from the plasma at the fundamental frequency (b). The references were the third-order mercury lines Hg 3543.08 Å and Hg 3524.19 Å, the positions of which for the working first order corresponded to wavelengths 10629.24 and 10572.57 Å.

shown that the line-intensity maximum has a wavelength larger than $\lambda_{2\omega_0}=0.5\lambda_0=\pi c/\omega_0=5300$ Å (red shift). Figures 2a and 2b illustrate typical spectrograms corresponding to the minimum shift $\Delta\lambda=2.3$ Å and the maximum shift $\Delta\lambda=8.3$ Å. On all the second-harmonic spectrograms we observed an asymmetrical broadening towards the red side. The degree of asymmetry, i.e., the ratio of the red half-width to the blue half-width, ranged from 1.06 to 1.65 at the half-intensity level and from 1.16 to 1.41 at the level corresponding to 0.1 of the maximum intensity. Large shifts of the maximum of the second-harmonic line corresponded as a rule to large degrees of asymmetry.

A red shift of the second harmonic was reported in[6,7] for laser pulses of picosecond duration, and asymmetrical broadening of the second-harmonic spectrum was observed in[7-9]. The broadening observed in[6] was symmetrical.

The theory of parametric resonance[2] offers a possibility of determining the dependence of shift of the intensity maximum of the second-harmonic line on such plasma parameters as the electron temperature T_e, ion content, and radiation flux q.[10] A comparison of the experimentally measured shift of the maximum of the second-harmonic line with the theoretical formula makes it possible to determine the temperature T_e for a given target and for a given laser-radiation flux.

Second-harmonic generation is due to excitation of parametric instability in the vicinity of the critical point $x=0$, at which the local plasma frequency $\omega_p(x)$ coincides with the frequency ω_0 of the laser radiation, i.e., $\omega_p(0)=\omega_0$. The largest red shift of the maximum of the intensity of the second-harmonic line is the result of coalescence of parametrically-excited longitudinal electron oscillation with one of the light waves (incident, scattered, or excited by stimulated Mandel'shtam-Brillouin scattering). The magnitude of the red shift $\Delta\omega$ is determined by the difference between the laser emission frequency and the frequency of the longitudinal electron wave. In the case when the detuning $\Delta\omega_0=\omega_0-\omega_p(x)\approx\omega_0(x/2a)$ (a is the characteristic dimension of the plasma inhomogeneity) is larger than the long-wave ion-sound oscillations, the red shift $\Delta\omega$ is determined by the expression (cf.[2], Eq. (9.9))

$$\Delta\omega=\sqrt{3}\,\omega_{Li}\left[\frac{v_{Te}^2}{c^2}+\frac{1}{4}\frac{v_E^2}{c^2}\frac{\omega_0}{\Delta\omega_0(x)}\right]^{1/2}. \tag{1}$$

Here ω_{Li} is the ion Langmuir frequency, v_{Te} is the thermal velocity of the electron, c is the speed of light, v_E is the amplitude of the velocity of the electron oscillations in the field of the incident light wave. Since the structure of the electromagnetic wave near the critical-density point is described by an Airy function,[11] the characteristic dimension in formula (1) can be chosen to be $(c^2a/\omega_0^2)^{1/3}$, which is of the order of the distance between the first maximum of this function and the critical point.

For a plasma produced by neodymium-laser radiation, formula (1) can be represented by the relation

$$\Delta\lambda\equiv\frac{\Delta\omega}{4\omega_0}\lambda_0\approx\left(\frac{Z}{A}\right)^{1/2}[20T_e+7\cdot10^{-15}q(a/\lambda_0)^{2/3}]^{1/2}, \tag{2}$$

between the red shift $\Delta\lambda$, measured in angstroms, and the electron temperature T_e (in keV), the energy flux of the incident light wave q (in W/cm^2), the characteristic dimension a of the inhomogeneity, the atomic number A, and the charge Z of the target material.

Formula (2) enables us, knowing the shift of the maximum of the second-harmonic line intensity, to determine the plasma electron temperature in a range of fluxes q in which the first term of (2) is not small in comparison with the second. At larger fluxes, when the second term predominates, the shift $\Delta\lambda$ ceases to depend on the plasma temperature.

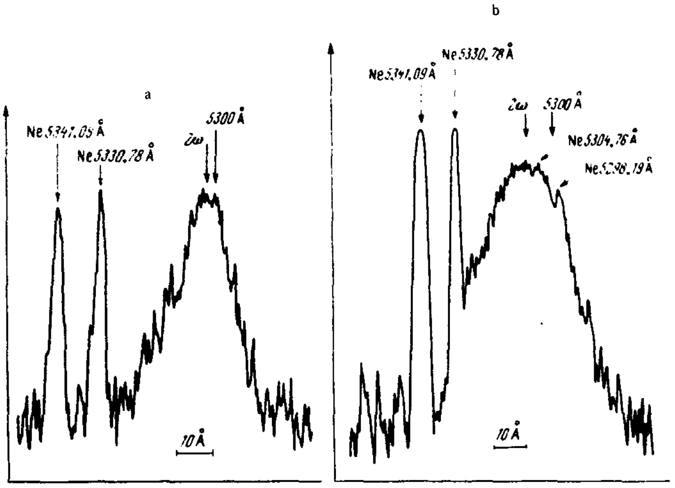

FIG. 2. Typical spectrograms of the second-harmonic line of the heating radiation in the light reflected from the plasma for shift values 2.3 Å (a) and 8.3 Å (b). The references were the neon lines Ne 5341.09 Å and Ne 5330.78 Å.

In experiment, a light flux $q = 2\times10^{14}$ W/cm^2 on an aluminum target ($A = 27$, $Z = 13$) corresponded to a shift $\Delta\lambda = 5$ Å (the dimension of the focal spot was $a \sim 100$ μ). From formula (2) we obtain $T_e \approx 1$ keV. This estimate of the plasma electron temperature turns out to be close to the value obtained by other measurement methods (cf.[5]).

[1] N. G. Basov and O. N. Krokhin, Zh. Eksp. Teor. Fiz. **46**, 171 (1964) [Sov. Phys.-JETP **19**, 123 (1964)]; Vestnik AN SSSR, No. 6, 55 (1970).

[2] V. P. Silin, Parametricheskoe vozdeĭstvie izlucheniya bol'shoĭ moshchnosti na plazmu (Parametric Action of High Power Radiation on a Plasma), Nauka, 1973.

[3] N. G. Basov, O. N. Krokhin, G. V. Sklizkov, S. I. Fedotov, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. **62**, 203 (1972) [Sov. Phys.-JETP **35**, 109 (1972)].

[4] K. Büchl, K. Eidman, A. Salzmann, and R. Sigel, Appl. Phys. Lett. **20**, 231 (1972); D. Beland, C. DeMichels, M. Mattioli, and R. Popular, Appl. Phys. Lett. **21**, 52 (1972).

[5] A. A. Rupasov, G. V. Sklizkov, V. P. Tsapenko, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. **65**, 1898 (1973) [Sov. Phys.-JETP **38**, 947 (1974)]; N. G. Basov, O. N. Krokhin, V. V. Pustovalov, A. A. Rupasov, V. P. Silin, G. V. Sklizkov, V. T. Tikhonchuk, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. **67**, 118 (1974) [Sov. Phys.-JETP **40**, 61 (1975)]; O. N. Krokhin, Yu. A. Mikhaĭlov, V. V. Pustovalov, A. A. Rupasov, V. P. Silin, G. V. Sklizkov, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. **69**, 206 (1975) [Sov. Phys.-JETP **42**, No. 1 (1975)].

[6] L. M. Goldman, J. Soures, and M. J. Lubin, Phys. Rev. Lett. **31**, 1184 (1973).

[7] P. Lee, D. V. Giovanelli, R. P. Godwin, and G. H. Call, Appl. Phys. Lett. **24**, 406 (1974).

[8] J. L. Bobin, M. Decroisette, B. Meyer, and Y. Vitel, Phys. Rev. Lett. **30**, 594 (1973); A. A. Gorokhov, V. D. Dyatlov, R. N. Medvedev, A. D. Starikov, and V. G. Tuzov, ZhETF Pis. Red. **21**, 111 (1975) [JETP Lett. **21**, 49 (1975)].

[9] M. Decroisette, B. Meyer, and Y. Vitel, Phys. Lett. **45A**, 443 (1974).

[10] V. V. Pustovalov, V. P. Silin, A. N. Starodub, and V. T. Tikhonchuk, Paper at Second Internat. Conf. on Plasma Theory, Kiev, 1974.

[11] V. L. Ginzburg, Rasprostranenie élektromagnitnykh voln v plazme (Propagation of Electromagnetic Waves in a Plasma), Fizmatgiz, 1961 [Pergamon].