Raman scattering as a diagnostic method for laser plasma

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The results of the experimental study of Raman scattering of probing radiation produced as a result of spherical laser heating of shell targets in the Kal'mar facility are given. The second harmonic of Nd laser is used to probe the plasma. The generation of the $3/2\ \omega_0$, $5/2\ \omega_0$, and $3\omega_0$ harmonics (ω_0 is the frequency of the Nd laser) is recorded.

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An effective method of diagnosing dense plasma "corona" heated by high-power optical pulsed radiation[1] involves investigation of scattered radiation of an auxilliary laser.[2] In this paper we propose a new method for nonstationary superdense plasma, which allows by using Raman scattering (see, for example, Ref. 3) of the probing radiation to estimate the shape of the spectrum and the level of plasma oscillation at certain points of the plasma "corona" profile with a specified density, and to determine the relative contribution to the absorption of each nonlinear process.

The experiments were carried out by using a nine-channel neodymium "Kal'mar" laser.[1] The laser radiation was focused on a shell target placed in the vacuum cham-

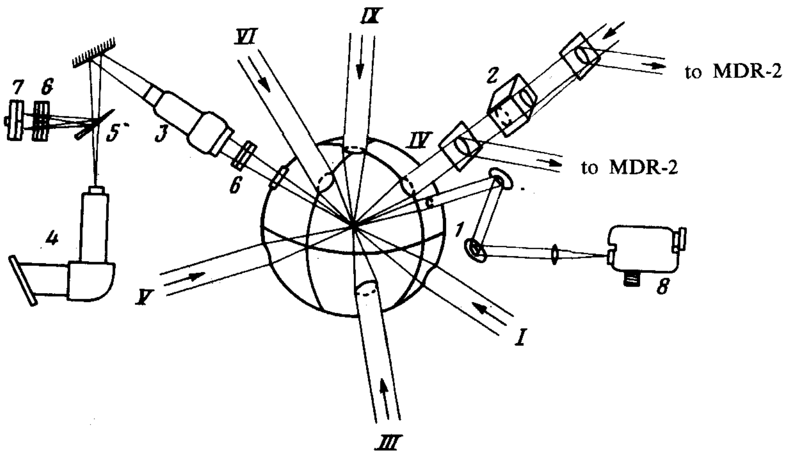

FIG. 1. Distribution of the heating beams (Roman numerals) and of the spectral diagnostic equipment: 1—vacuum chamber; 2—KDP crystal; 3—lens; 4—ISP-51 spectrograph; 5—wedge; 6—light filters; 7—casettes; 8—DMR-4 monochromator.

ber (Fig. 1). The pulsewidth at the base was ~2.5 nsec. The plasma was probed by the second harmonic of the pumping radiation, which was generated in a KDP crystal (2) placed in one of the nine beams. The laser energy was 200 J, which for a ~150-μm-diam focus spot corresponded to the flux density $q_0 \approx 2 \times 10^{14}$ W/cm^2. The energy of the probe radiation was ~1 J at $q_1 \approx 2 \times 10^{12}$ W/cm^2. The spectrum width of the heating and probing radiation was ~5 Å at half intensity. The scattered radiation was investigated in two recording channels. In the first channel, which was directed at an angle of 105° to the axis of the probing beam, the target image was projected by a lens (3) (Fig. 1) on the slit of an ISP-51 spectrograph (4), which recorded radiation in the range that included the $3/2\omega_0$, $2\omega_0$, and $5/2\omega_0$ frequencies (ω_0 is the frequency of heating radiation). The spectrograph slit, which was placed in the scattering plane of the probing beam, crossed the center of the target image (see Fig. 2d). The spatial resolution was ~15 μm. In addition, the target images were recorded at frequencies near $3/2\,\omega_0$ and $2\omega_0$, which were isolated by the light filters (5), (6), and (7) (Fig. 1). The plasma radiation at a frequency near $3\omega_0$ was recorded in the second channel at an angle of 25° relative to the axis of the probing beam (8) (Fig. 1).

Generation of the $5/2\omega_0$ radiation was observed during the heating of glass and polystyrene shell targets in the presence of probing radiation (Fig. 2c). This radiation has a two-component structure and is confined, as a rule, to two regions of the plasma corona (*A* and *B* in Fig. 2c); it is in that part of the corona which is subjected to the probing radiation. This radiation was not recorded in the absence of the probing light. The spectrum width of the radiation at the 0.1 $I_{\max}$ level is ~30–40 Å, and the spacing between the spectral components is ~19 Å.

As before,[4] the $3/2\omega_0$ harmonic generation occurs in the absence of the probing radiation at $q_0 \approx 2 \times 10^{14}$ W/cm^2. In its presence the $3/2\omega_0$ harmonic spectrograms

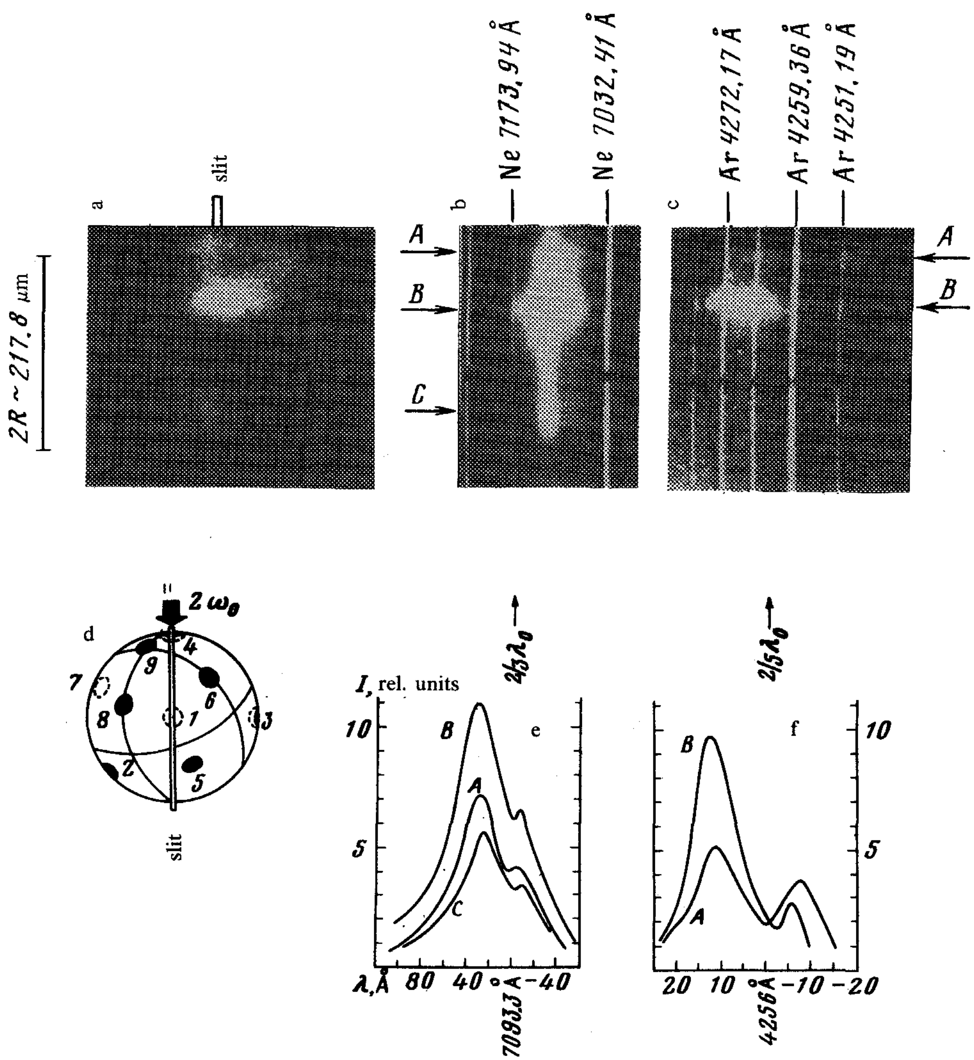

FIG. 2. Photograph of the plasma corona in the radiation near $3/2\,\omega_0$ (a). Spectrograms and spectral distributions of the radiation intensity of the plasma near $3/2\,\omega_0$ (b,e) and $5/2\,\omega_0$ (c, f). Location of the spectrograph slit according to the target image (d) (the numbers indicate the optical axes of the laser beams; the probing radiation is indicated by the arrow). The target is a hollow $(C_8D_8)_n$ microsphere $2R \approx 217.8\ \mu m$ in diameter, and $\Delta R \approx 2.1\ \mu m$ wall thickness.

contain, in addition to the radiation near the $5/2\omega_0$ frequency, additional emission lines that are localized in the plasma corona in the same way as those in the case of emission at the $5/2\omega_0$ frequency. Figure 2b shows this spectrogram in the $3/2\omega_0$ range. The spectral intensity distributions for the three emission regions are shown in Fig. 2d, two of which (*A* and *B*) correspond to the emission regions near $5/2\omega_0$ (Fig. 2c). The additional emission near the $3/2\omega_0$ frequency (like near the $5/2\omega_0$ frequency) has a two-component structure with the total width of ~ 185 Å at the 0.1 $I_{\max}$ level and with the spacing between the components of ~ 37 Å. The brightness of the additional emission in the direction of recording is of the same order or greater than that of the self-radiation of the $3/2\omega_0$ harmonic, which for the region C (Figs. 2a and b) is $\sim 5 \times 10^6$ W/cm^2·sterad.

In the case of spectrograms in Figs. 2b and c, the energy in the auxilliary radiation in the $3/2\omega_0$ region is approximately 50 ± 15-fold greater than that in the radiation near the $5/2\omega_0$ region. The radiation near the $3\omega_0$ frequency, which was recorded in the second channel, has a single-component spectral structure with the width of $\lesssim 5$ Å (at the 0.5 $I_{\max}$ level) and a maximum that is shifted, with respect to the exact value of $(\frac{1}{3})\lambda_0 = 3546.7$ Å by ~ 3 Å, in the direction of longer wavelengths.

The recording of scattered radiation at the $3/2\omega_0$, $5/2\omega_0$, and $3\omega_0$ frequencies indicates that the plasma has intensive fluctuations of longitudinal Langmuir waves at frequencies of ω_0 and $(\frac{1}{2})\omega_0$, which are excited in the region of the critical n_c and quarter-critical $n_c/4$ densities, respectively (for the Nd laser $n_c \approx 10^{21}$ cm^{-3}). We note that the presence of intensive Langmuir waves in the $n_c/4$ density region for the CO$_2$ laser radiation ($\approx 2.5 \times 10^{18}$ cm^{-3}) was established earlier.[5]

The presence of the two-component structure at the frequencies of fractional harmonics ($3/2\omega_0$ and $5/2\omega_0$) confirms that plasma emission occurs in the region of the 1/4-critical density.[4,6] The two-component structure is associated with the scattering of the probing or heating radiation by the plasma waves in the bulk of the plasma (blue satellites) and outside the plasma (red satellites). The spacing between the satellites in the $3/2\,\omega_0$ spectrum should be 1.6 fold greater than the corresponding value for the $5/2\,\omega_0$ harmonic, which is consistent with the experimentally observed ratio $\Delta\lambda_{3/2}/\Delta\lambda_{5/2} \approx 1.9$. The equation relating $\Delta\lambda_{3/2}$ to the electron temperature T_e [6] gives an average value $T_e = 0.5 - 0.6$ keV with respect to duration of the heating pulse in the $n_c/4$ region.

The intensity of the scattered radiation is determined by the spectral energy density of the Langmuir waves $W_l(k_l)$. Therefore, a simultaneous measurement of the

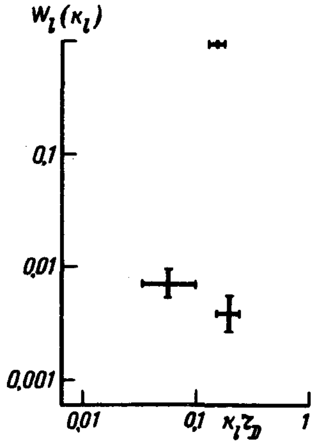

FIG. 3. The result of reconstruction of the spectrum of plasma turbulence in the $n_c/4$ region from the data of the experiment ($T_e \approx 0.5$ keV, r_D is the Debye electron radius).

intensities of the 3/2 ω_0 and 5/2 ω_0 lines of the Raman-scattered probing radiation and of the 3/2 ω_0 harmonic makes it possible to reconstruct the dependence of W_l on the wave number of the Langmuir waves k_l. Figure 3 shows the result of analyzing the experimental data under the assumption that the excited turbulence is isotropic. The experimentally measured brightness of the plasma radiation at the 3/2 ω_0 frequency makes it possible to estimate the total field strength of the Langmuir waves E_l in the $n_c/4$ region. For the parameters in our experiment ($T_e \approx 0.5$ keV, plasma inhomogeneity size $L \approx 20$–$30\ \mu$m) we obtain $E_l \approx 0.3E_0$. This estimate of E_l is consistent with the current theoretical results[7] and indicates that less than 10% of the energy of heating radiation is absorbed in the $n_c/4$ region due to parametric instabilities.

As regards the 3 ω_0 radiation, the small width of the spectrum makes it possible to associate its generation with the scattering of the probing radiation by the ordered structure of the Langmuir plasma waves in the n_c region, which are produced as a result of linear transformation of the heating radiation.[8]

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