Laser-plasma diagnostics in the critical-density region using the method of Raman scattering

N. G. Basov, M. V. Osipov, A. A. Rupasov, G. V. Sklizkov, and
A. S. Shikanov
P. N. Lebedev Physics Institute, USSR Academy of Sciences

(Submitted 29 December 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 4, 210–214 (20 February 1981)

Raman scattering of probing light was used for the first time to investigate a plasma in the region of critical density $n_c \approx 10^{21}$ cm^{-3} for neodymium-laser heating radiation. The nonlinear processes that occur in the plasma in the n_c region are identified on the basis of an examination of the scattering spectrum of the probing light.

PACS numbers: 52.50.Jm, 52.70.Kz

Studies of the generation of the $2\omega_0$ harmonic in a laser plasma have made it possible to propose and use[1] several methods of plasma diagnostics in the vicinity of the critical density n_c, which are based on a measurement of the characteristics of harmonic radiation. In addition to these methods of "passive" diagnostics, however, the "active" diagnostics, which are based on Raman scattering of the probing radiation, acquire a special role for obtaining more detailed information about nonlinear processes in the vicinity of n_c, in particular, for plotting the plasma-turbulence spectrum. Obtaining information about the plasma-turbulence spectrum is very important for determining the quantitative contribution to laser-energy absorption and to the generation of fast particles of each mechanism of anomalous interaction of high-power radiation with the plasma. The efficiency of the Raman-scattering method for plasma diagnostics in one-fourth $n_c/4$ of the critical density region was determined in the experiments performed using the Kal'mar facility. We used this method to study a plasma in the n_c region for the frequency of a heating laser.

The experiments were conducted using a nine-beam "Kal'mar" neodymium laser. The laser radiation was focused on a shell target of polystyrene $(C_8D_8)_n$, which was placed in a vacuum chamber (Fig. 1). The pulse duration was ≈ 1 nsec at the half-intensity level. The plasma was probed with radiation of the second harmonic of the frequency of the heating light, which was obtained by frequency doubling in a KDP crystal (3) in one of the laser beams. The laser energy was 200 J, which corresponded to a flux density $q_0 \approx 2\times 10^{14}$ W/cm^2 for a focusing-spot diameter of ≈ 150 μm. The energy of the probing radiation was ≈ 1 J for $q_1 \approx 2\times 10^{12}$ W/cm^2. The width of the heating- and probing-radiation spectrum was ≈ 5 Å at the half-intensity level. The scattered radiation near the frequency 3 ω_0 was examined at an angle of 25° to the axis of the probing beam; this corresponded to a scattering angle $\theta_r \approx 155°$. The target image was transferred in this direction to the slit of the DMR-4 spectrograph (4) with a dispersion of ≈ 50 Å/mm in the investigated frequency range. Figure 1 also shows other observation directions in which the combination frequencies of the scattering of

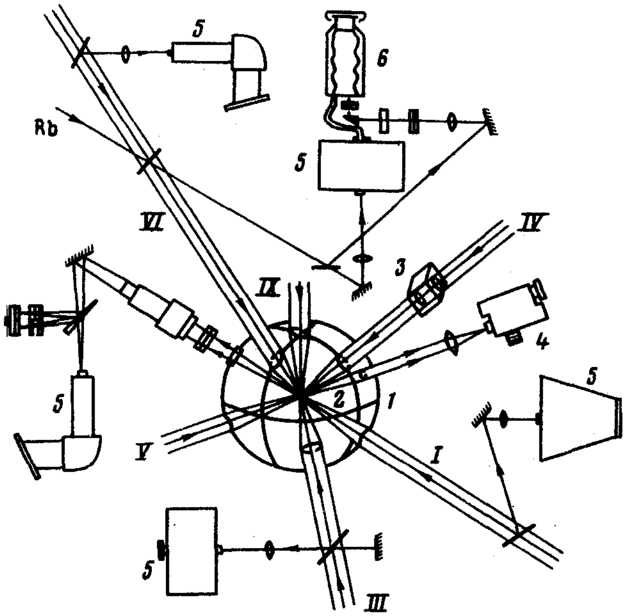

FIG. 1. Schematic of the arrangement of the diagnostic equipment. 1, Vacuum chamber; 2, target; 3, KDP crystal; 4, DMR-4 monochromator; 5, other spectral instruments; 6, photoelectron recorder. The heating beams are denoted by Roman numerals.

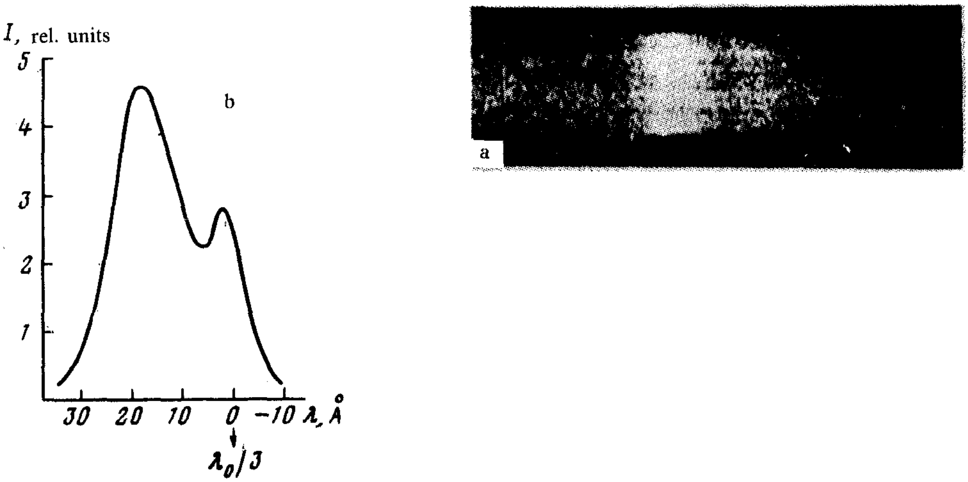

FIG. 2. Spectrogram and spectral distribution of the intensity of the radiation near the frequency $3\omega_0$ for a $(C_8D_8)_n$ target with a diameter $2R \approx 196.8$ μm and wall thickness $\Delta R \approx 3.8$ μm.

the probing radiation in the $n_c/4$ region and the spatially and time-resolved harmonics of the heating light ($3/2$ ω_0 and $2\omega_0$) generated in the plasma were recorded.

The radiation near the frequency $3\omega_0$ with a pronounced, two-component spectral structure was observed in the scattering spectrum of the probing beam. Both spectral components of the spectrogram shown in Fig. 2 are "red"-shifted relative to the exact value of $\lambda_0/3 \approx 3546.7$ Å, the right-hand component by 2.5 Å and the left-hand component, which is more intense and broader, by 18.5 Å. The width of the spectrum at the half-intensity level is ≈ 15 Å (Fig. 2). As the flux density of the heating radiation decreased, the left-hand component of the spectrum disappeared and only the right-hand component (slightly shifted component) remained.

The radiation was not detected near the frequency $3\omega_0$ in the absence of the probing wave. This is a normal occurrence at these heating-radiation flux densities. In fact, the $3\omega_0$ harmonic can appear in the plasma because of four-wave merging processes of the plasma waves and the transverse pumping wave in the critical-density region ($3l \rightarrow t_3$, $2t_0 + l \rightarrow t_3$, and $2l + t_0 \rightarrow t_3$), which are higher order processes than the three-wave interaction. They are realized at much higher flux densities.[3] The merging process of the $2\omega_0$ harmonic generated in the plasma with the plasma oscillations ($t_2 + l \rightarrow t_3$) also has low probability because of the low probability of transformation ($\sim 10^7$) of the laser radiation into the $2\omega_0$ harmonic in the plasma. Therefore, there is no doubt that the observed radiation near the frequency $3\omega_0$ is the result of Raman scattering of the probing wave by plasmons that are produced by the heating radiation in the n_c region ($t_{2\,\mathrm{probe}} + l \rightarrow t_3$). We note that the scattering of the probing wave in the plasma generally occurs within a wide range of electron densities $n_e \lesssim 4n_c \approx 4 \times 10^{21}$ cm^{-3}. However, the appearance of radiation in the scattering spectrum, which is frequency-shifted relative to the probing wave by an amount ω_0 equal to the electron Langmuir frequency ω_{Le} for the n_c region, indicates that the intensity of plasma oscillations increases sharply in this region. The threshold nature, in terms of pumping flux, of the broader, left-hand component of the radiation spectrum near $3\omega_0$ makes it possible to relate it to the scattering of the probing wave by parametrically excited plasmons ($t_0 \rightarrow l + s$). The shift of this component with respect to $3\omega_0$ in this case is determined by the frequency shift $\Delta\omega$ of the plasmons relative to ω_0, which is equal to the frequency of the ion-sound oscillations $\Delta\omega \approx \omega_s(k_s)$. On the other hand, the small width and shift of the right-hand component with respect to $\lambda_0/3$ indicate that it occurs because of scattering of the probing wave by plasma oscillations that appear as a result of linear transformation of the transverse pumping wave. The shift $\Delta\lambda_3$ of this component can be explained by the Doppler effect as the scattering region n_c moves with a velocity u, which can be determined from the formula $\Delta\lambda_3/\lambda_0 \approx (5/9)u/c$ by measuring $\Delta\lambda_3$, where λ_0 is the pump wavelength and c is the velocity of light. According to this expression, the "red" shift $\Delta\lambda_3 \approx 2.5$ Å (Fig. 2) corresponds to a velocity $u \approx 1.3 \times 10^7$ cm/sec of the n_c region toward the target center as a result of compression of the shell target by the laser pulse, in good agreement with the results obtained by using other methods.[4]

The similarity of the spectrum near the frequency $3\omega_0$ and the spectrum of the $2\omega_0$ harmonic generated in the plasma[1] is attributable to the fact that these radiations appear in the same n_c region as a result of Raman scattering of the probing and heating radiations, respectively, by plasma waves of indentical nature.

For the probing and recording geometry used by us, the wave number of the plasmons that scatter the probing wave with the formation of $3\omega_0$ radiation is equal to $k_l \approx 4.45\omega_0/c$. The other Raman scattering frequency of the probing radiation in the n_c region is ω_0, which is identical to the frequency of the heating light (the corresponding plasmon wave number is $k_l \approx 1.73\omega_0/c$). This makes it impossible to detect this radiation against the background of the much more intense plasma-reflected pumping wave even in the presence of spatial resolution. The intensity of the narrow component of the spectrum of the $2\omega_0$ harmonic,[1] which is generated in the n_c region due to scattering of the heating wave by plasmons with $k_l \approx 1.73\omega_0/c$, can be measured only in the absence of probing radiation because of the coincidence of their frequencies. To plot the plasma-turbulence spectrum in the n_c region with use of the given probing radiation, we must obtain the required range of variation of the wave numbers of the scattering plasmons by varying the scattering angle θ_r, if there are several directions for recording the radiation near the frequency $3\omega_0$.

[1] N. G. Basov, V. Yu. Bychenkov, O. N. Krokhin, M. V. Osipov, A. A. Rupasov, V. P. Silin, G. V. Sklizkov, A. N. Starodub, V. T. Tikhonchuk, and A. S. Shikanov, Kvantovaya Elektron. **6**, 1829 (1979) [Sov. J. Quantum Electron. **9**, 1081 (1979)]; Zh. Eksp. Teor. Fiz. **76**, 2094 (1979) [Sov. Phys. JETP **44**, 1059 (1979)].

[2] N. G. Basov, V. Yu. Bychenkov, N. N. Zorev, M. V. Osipov, A. A. Rupasov, V. P. Silin, G. V. Sklizkov, A. N. Starodub, V. T. Tikhonchuk, and A. S. Shikanov, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 439 (1979) [JETP Lett. **30**, 409 (1979)]; N. G. Basov, V. Yu. Bychenkov, M. V. Osipov, A. A. Rupasov, V. P. Silin, A. S. Shikanov, G. V. Sklizkov, A. N. Starodub, V. T. Tikhonchuk, and N. N. Zorev, Phys. Lett. A **77**, 163 (1980).

[3] J. S. Hildum, Preprint KMS-U 121, 1973.

[4] N. G. Basov, P. P. Volosevich, E. G. Gamaliĭ, S. Yu. Gus'kov, A. A. Erokhin, Yu. A. Zakharenkov, N. N. Zorev, A. A. Kologrivov, V. B. Rozanov, A. A. Rupasov, A. A. Samarskiĭ, G. V. Sklizkov, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. **78**, 420 (1980) [Sov. Phys.–JETP **51**, 212 (1980)].

Translated by Eugene R. Heath.
Edited by S. J. Amoretty