Investigation of plasma turbulence by a Raman scattering method

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(Submitted 13 April 1983)
Zh. Eksp. Teor. Fiz. **85**, 919–931 (September 1983)

Raman scattering of probing emission is used for the first time ever to investigate a laser plasma in the regions of the critical and quarter-critical densities (n_c and $n_c/4$) for the heating emission of a neodymium laser ($n_c \approx 10^{21}$ cm^{-3}). Investigation of the scattering spectra of the probing and heating emissions permits identification of the nonlinear processes that develop in these regions and yields the spectral distribution of the energy of the plasma waves produced in two-plasmon decay instability.

PACS numbers: 52.70.Kz, 52.35.Ra, 52.35.Mw, 52.25.Ps

1. RAMAN SCATTERING AS A METHOD OF INHOMOGENEOUS PLASMA DIAGNOSTICS

Measurement of the energy, spectral, temporal, and angular properties of the $2\omega_0$ and $3\omega_0/2$ harmonics (ω_0 is the laser-emission frequency) generated in a plasma in the regions of critical (n_c) and quarter-critical ($n_c/4$) densities, respectively, permits diagnostics of a host of plasma parameters and their evolution during the action of the laser pulse.[1–5] The localization of the onset of these harmonics near the n_c and $n_c/4$ regions makes it possible to determine the values of the plasma parameters for just those regions which are most important when high-power laser radiation interacts with matter.[6]

At the same time, to obtain more detailed information on the nonlinear processes in the n_c and $n_c/4$ regions we must have information on the spectral distribution of the energy of the plasma waves (plasmons) excited both as a result of parametric instabilities[7,8] and via linear transformation of heating emission.[9] Information on the spectral distribution of the plasma oscillations is very important for the determination of the quantitative contribution made to the absorption of the laser energy and to the generation of fast particles by each of the evolving mechanisms of nonlinear interaction of the powerful radiation with the plasma.

By measuring the coefficients of conversion of laser radiation into the $2\omega_0$ and $3\omega_0/2$ harmonics one can estimate the intensity of only the long-wave Langmuir oscillations $k_l \sim k_0$ (k_l and k_0 are respectively the wave numbers of the plasmons and of the laser radiation). The electron energy absorption and acceleration, however are due to the shorter-wavelength oscillations $k_l r_{De} \lesssim 1$ (r_{De} is the Debye radius of the electron). Diagnostics of such oscillations by the Raman scattering (RS) method calls for the use of shorter-wavelength probing emission. Such a use of RS with the aid of an additional laser beam is already a method of "active" diagnostics, in contrast to the aforementioned method of RS of the heating emission (generation of harmonics), which is "passive."

It follows from classical scattering theory that under conditions when the scattering parameter

$$\alpha=(k''r_{De})^{-1}\gg 1,$$

$$(k''=|\mathbf{k}_{pr}-\mathbf{k}'|\approx 2k_{pr}\sin\theta_s/2,$$

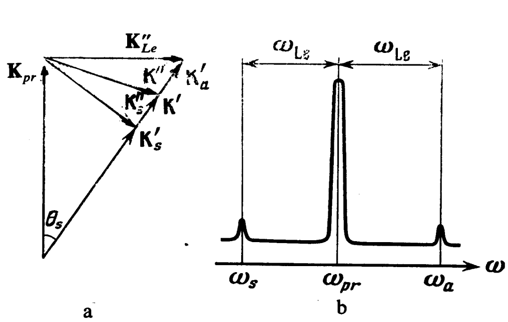
where $\mathbf{k}_{pr}$ and $\mathbf{k}'$ are the wave vectors of the probing and scattering waves and θ_s is the scattering angle) the spectrum of radiation scattered in a plasma having an electron density n_e consists of a central ionic component that has the same frequency as the probing emission (ω_{pr}) and is due to scattering by ions, and two electronic satellites, Stokes and anti-Stokes, separated from the probing frequency by the electron Langmuir frequency ω_{Le} corresponding to the given density ($\omega_{Le} \approx (4\pi n_e e^2/m)^{1/2}$, where e and m are the electron charge and mass):

$$\omega_s'\approx\omega_{pr}-\omega_{Le}(n_e) \text{ and } \omega_a'\approx\omega_{pr}+\omega_{Le}(n_e)$$

(Fig. 1).[10,11] These satellites are due to scattering of the probing emission by the thermal fluctuations of the electron density. In an equilibrium plasma the intensities of the satellites are smaller by a factor α^2 than that of the ion component of the scattering. If, however, plasma turbulence is produced by the heating emission, the level of the charge-density fluctuations increases strongly because of buildup of plasma oscillations. The satellite intensity should then increase substantially. The intensity of the electronic scattering satellites is connected with the spectral energy density $W_l(k_l)$ of the Langmuir waves by the relation[12,13]

$$\frac{dq'}{d\omega'\,do'}\approx cq_{pr}\left(\frac{\omega'}{\omega_{pr}}\right)^2 k_l^2 W_l(k_l), \tag{1}$$

where $dq'/d\omega' do'$ is the energy flux density of the scattered radiation in the frequency interval $d\omega'$ and in the solid angle do', c is a factor that depends on the angle between the polar-



a b

FIG. 1. a) Arrangement of wave vectors of the probing ($\mathbf{k}_{pr}$) and scattered ($\mathbf{k}'_{s,a}$) emissions, as well as of the plasma oscillations ($\mathbf{k}''_{s,a}$); b) shape of scattering spectrum of probing emission in a homogeneous plasma in the case $\alpha + (k''r_{De})^{-1}1$.

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ization vectors of the probing and scattered radiation, on the scattering angle, on the characteristic size of the inhomogeneity of the density in the scattering and on the value of the electron density in this region, q_{pr} is the probing-wave flux density, ω' and ω_{pr} are the frequencies of the scattered and probing emission, and k_l is the wave number of the scattering plasmons. Measurement of the intensity of the electronic satellites in the scattering spectrum of the probing wave yields therefore, when account is taken of (1), the spectral energy density $W_l(k_l)$ of plasma waves with wave numbers $k_l = k''_a$ and $k_l = k''_s$. The values of k''_a and k''_s are determined from the momentum conservation law for the Raman scattering process (Fig. 1a).

This method of "active" diagnostics permits, in principle, reconstruction of the entire Langmuir turbulence spectrum $\omega_l(k_l)$. To ensure a wide range of variation of k_l, however, it is necessary to investigate the intensity of the satellites in the scattering spectrum in all possible directions, as well as use probing emission with variable wavelength.

Experiments with Raman scattering of the probing emission have come into use for "active" diagnostics of plasma turbulence only recently. There are only a few known published papers on this topic.[14–19] In the first two of these papers the plasma was produced by CO_2 laser radiation incident on a gaseous[14] or solid[15] target. Under the conditions of Refs. 14 and 15 no radiation at half-integer harmonics was observed, and Raman scattering of *ddd* probing wave was the only method for diagnostics of the processes in the region $n_c/4 \approx 2{,}5\cdot10^{18}$ cm^{-3}, which made possible to confirm development of two-plasmon decay instability excited by CO_2 laser emission. Since, however, the frequency of the probing emission used in these experiments (second harmonic of a neodymium laser in Ref. 15 and a ruby laser in Ref. 14) was many times larger than the frequency of the CO_2 laser heating emission, the following relation holds in the $n_c/4$ region for the frequencies of the electronic scattering satellites

$$\omega_a - \omega_s = 2\omega_{Le} = \omega_0 \ll \omega_a, \quad \omega_s \approx \omega_{pr}.$$

As a result, at all scattering angles the difference $(k''_a - k''_s)$ between the wave numbers is smaller than numbers themselves (Fig. 1a). For example, for the conditions[15]

$$k_a' \approx \frac{2\omega_{Nd}}{c} + \frac{1}{2}\frac{\omega_{CO_2}}{c} = 2{,}05\frac{\omega_{Nd}}{c},$$
$$k_s' \approx \frac{2\omega_{Nd}}{c} - \frac{1}{2}\frac{\omega_{CO_2}}{c} \approx 1{,}95\frac{\omega_{Nd}}{c}$$

and for scattering through an angle $\theta_s \approx 20°$ we obtain respectively $k''_a \approx 0{,}72\omega_{Nd}/c$ and $k''_s \approx 0{,}68\omega_{Nd}/c$. Therefore, from the experimental data of Refs. 14 and 15 we can determine the value of W_l in fact for only one given value: $k_l \approx k''_a \approx k''_s$ (for Ref. 15 this value is $k_l \simeq 0{,}7\omega_{Nd}/c \approx 7\omega_{CO_2}/c$). Moreover, we note that in Ref. 14, owing to properties of the recording apparatus, only one Stokes satellite was measured. In this respect, the Raman-scattering method provides in the experiments of Refs. 14 and 15 no more information than does the recording of the $3\omega_0/2$ harmonic, although it does yield the value of W_l in another, shorter-wavelength region of the plasma-turbulence region.

Much more information can be obtained by recording simultaneously both Raman-scattering lines (Stokes and anti-Stokes) and the line of the $3\omega_0/2$ harmonic, using probing emission frequency only a few times larger than that of the heating emission. This possibility of efficiently using the scattering of both the heating and the probing emission to construct the plasma-turbulence spectrum was proposed in experiments[15,17] in which the "Kal'mar" nine-beam neodymium-laser facility of the Lebedev Institute was used. Namely, by recording the scattered radiation simultaneously at three frequencies in the same direction, we obtain right away the values of W_l for three chosen values of k_l. Simultaneous recording of all three frequencies in the spectrum of the scattered radiation in several observation directions permitted an even more complete reconstruction of the turbulence spectrum in the $n_c/4$ region for neodymium-laser radiation ($n_c/4 \approx 2{,}5\cdot10^{20}$ cm^{-3}). We shall discuss below the results obtained by probing with the Kal'mar facility the region $n_c/4$ (Refs. 16, 17) and n_c (Refs. 18, 19) by the RS method, and present their interpretation.

2. MEASUREMENT OF THE PARAMETRIC TURBULENCE SPECTRUM IN THE VICINITY OF $n_c/4$

Experiments on the determination of the spectral distribution of plasma oscillations in the vicinity of $n_c/4$ (Refs. 16 and 17) were performed on the "Kal'mar" nine-beam neodymium laser at a heating emission energy 200 J and at a pulse duration $\tau_L \approx 1.5$ nsec. The plasma was probed with the pump-wave second harmonic obtained with a KDP crystal (labeled 2 in Fig. 2) placed in one of the laser beams. The energy of the probing emission was ≈ 1 J. The spectral widths of the heating and probing emission was $\simeq 5$ Å at the $I_{\max}/2$ level. Polystyrene and glass shell targets were investigated.

We note that the Raman scattering of the probing emission was investigated simultaneously with the $3\omega_0/2$ harmonic generated as a result of the Raman scattering of the heating emission itself in the $n_c/4$ region ($t_0 + l_{\omega 0/2} \to t_{3/2\omega 0}$). This is a characteristic feature that distinguishes these experiments from those cited above,[14,15] and yields additional points for the plotting of the plasma-turbulence spectrum, since plasmons with different wave numbers participate in the Raman scattering of the heating and probing beams.

The use of the second harmonic of the pump wave to probe the plasma in the $n_c/4$ region was dictated by two considerations. First, the frequency $2\omega_0$ of this probing emission is only double the frequency ω_0 of the heating emission, meaning also the difference between the Raman frequencies (anti-Stokes and Stokes) of the probing wave ($\Delta\omega = {}^5/_2\omega_0 - {}^3/_2\omega_0 = \omega_0$). As a result, at any scattering angle θ_s the difference between the plasmon wave numbers $(k''_a - k''_s)$ is no longer small compared with their values, unlike in the experiments of Refs 14 and 15. By measuring the intensities of the Raman scattering lines we can therefore determine the spectral energy density $W_l(k_l)$ of plasma waves with substantially differing wave numbers $k_l = k''_a$ and $k_l = k''_s$, i.e., we can plot the plasma-turbulence spectrum. Second, probing emission in the form of the second

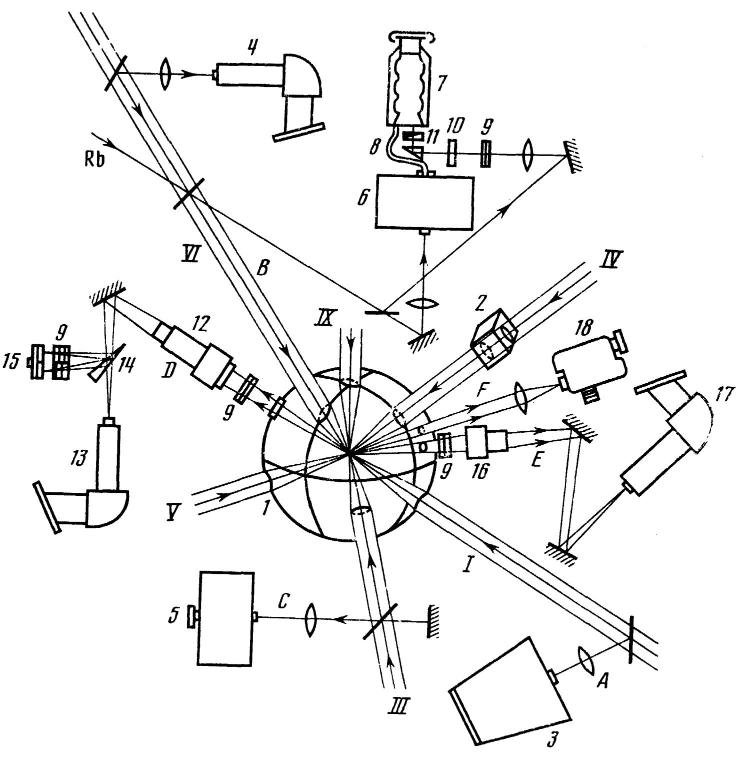

FIG. 2. Arrangement of the heating beam and of the diagnostic apparatus for the investigation of the emission of the harmonics and of the Raman scattering of the probing emission. *A, B, C, D, E, F*—recording channels; 1—vacuum chamber; 2—KDP crystal; 3–6, 14, 17, 18—spectrographs; 7, 8—photoelectronic recorder with light pipe; 9—light filters; 10—scatterer; 11—stepped attenuator; 12, 16—lenses; 14—optical wedge; 15—cassette. The Roman numbers label the heating beams.

harmonic of the pump wave can be easily obtained with a KDP crystal of sufficiently large aperture. It is important that this obviates the need for synchronizing such a probing beam with the heating beam.

The use of the second harmonic of the pump wave to probe the plasma has, however, the shortcoming that the Stokes component of the Raman scattering (in the $n_c/4$ region) of such a probing beam ($t^{pr}_{2\omega_0} + l_{\omega 0/2} \to t_{3/2\omega 0}$) has the same frequency as the anti-Stokes component of the Raman scattering of the heating beam itself ($t_0 + l_{\omega 0/2} \to t_{3/2\omega 0}$), i.e., of the harmonic $3\omega_0/2$. This raises certain difficulties in the measurement and identification of the intensities of these beams, which are of different nature, when they are simultaneously recorded. In the experiments of Refs. 16 and 17 these difficulties were overcome by recording the scattering spectra with spatial resolution. However, under the conditions of Refs. 16 and 17 the equality of the frequencies of these scattering components increased the experimental error of their relative intensities.

The arrangement of the diagnostic apparatus for the investigation of the scattered radiation in the "Kal'mar" facility is shown in Fig. 2. In the recording channels *D* and *E*, the target image was projected by lenses on the slits of prism spectrograph. The spatial resolution over the object was $\sim 15\ \mu$m. In addition, we used a system[14,15] that enabled us to record the plasma image at the frequencies $2\omega_0$ and $3\omega_0/2$ with the same spatial resolution. The angles between the recording channels *D* and *E* and the heating beam IV (see Fig. 2) in which the KDP crystal was placed were 105 and 42.5°, respectively, corresponding to scattering angles θ_s of the probing emission 75 and 137.5°. To make clear the target irradiation and the probing geometry as well as the observation direction, Fig. 3d shows the location of the spectrograph slit in accord with the channel image for the recording channel D (Fig. 2), corresponding to the probing-beam scattering angle $\theta_s \approx 75°$. The numbers label the points corresponding to the optical axes of the heating beams, while the dashed lines mark the beams on the rear target side relative to the observation direction. The probing emission is marked by an arrow.

When the spectrograph slit is placed in accord with the target image in such a way that the spectrograph slit passes through the probing region (as shown in Fig. 3d in both registration directions, the scattering spectrum for both glass and polystyrene shells revealed emission near the frequencies $5\omega_0/2$ and $3\omega_0/2$, displaced in the spectrum by an amount $\Delta\omega \approx \omega_0/2$ in opposite directions relative to the ion component of the probing wave, and localized in like fashion on the plasma-corona image in that part of the corona which is acted on by the probing emission. The emission near the frequency $3\omega_0/2$ was superimposed in the spectrograms on the $3\omega_0/2$ harmonic generated by the plasma as a result of the Raman scattering of the heating emission itself in the $n_c/4$ region. On the spectrograms with spatial resolution, however, these emissions near the frequency $3\omega_0/2$ were unambiguously identified, since they had somewhat different spectra and an entirely different spatial localization. In fact, the $3\omega_0/2$ harmonic produced in the plasma by the heating emission is generated in the entire plasma corona, and the additional emission near the $3\omega_0/2$ frequency is emitted only by the probed section of the corona. We note that in the absence of probing emission we observed (in channel *D*, Fig. 2), *at the* sensitivity limit of the receiving apparatus, emission near the frequency $5\omega_0/2$, resulting from a process of lower order of smallness, wherein two pump photons merge with a plasmon in the vicinity of $n_c/4$ ($t_0 + t_0 + l_{\omega 0/2} \to t^{5}{}_{/2\omega 0}$). The intensity of this emission, however, was approximately 1/30th of the intensity of the emission produced near $5\omega_0/2$ by the probing emission.

Figure 3c shows one of the emission spectrograms near $5\omega_0/2$, obtained in experiments 16,17 on a $(C_8D_8)_n$ target at a probing wave angle $\theta_s \approx 75°$. Figure 3e shows the spectral distributions of the intensity of this emission for two regions of its spatial localization on the image of the plasma corona (levels A and B on Fig. 2), corresponding to the probed section of the target. One can see clearly a two-hump spectrum with distance $\delta\lambda_{5/2} \approx 19$ Å between the peaks. Fig. 3b shows a spectrogram of the emission near $3\omega_0/2$, recorded during the same shot and for the same observation direction. It can be seen that it is a superposition of the $3\omega_0/2$ harmonic generated in the entire corona and of additional emission at this frequency (levels A and B in Fig. 2) and localized in the plasma corona in analogy with the emission near $5\omega_0/2$. This emission has likewise a double-hump spectrum with distance $\delta\lambda_{3/2} \approx 37$ Å between the peaks and with width ≈ 185 Å at the $I_{\max}/10$ level. Such a superposition is clearly seen also on the photograph of the plasma corona in emission near the frequency $3\omega_0/2$ (Fig. 3a), as separate by a set of appropriate light filters. It follows from the reduction of this photograph that the brightness of the additional emission in the recording direction is of the same order or even higher than the brightness of the $3\omega_0/2$ harmonic proper, the latter being $\approx 5\times 10^6$ W.cm^2·sr for region C of Figs. 3a and 3b. In turn, comparison of the spectrograms of Figs. 3b and 3c shows that the energy contained in the additional emission near the frequency $3\omega_0/2$ is approximately 50 ± 15 times larger than the energy contained in the $5\omega_0/2$ emission.

The described features of the emission at $3\omega_0/2$ and $5\omega_0/2$, observed by probing the plasma, allow us to attribute them to Raman scattering of the probing emission. The probing wave is scattered in the plasma in a wide range of electron densities. The appearance in the scattering spectrum of electronic satellites shifted by an amount $\Delta\omega \approx \omega_0/2$ relative to the ionic component is evidence of an abrupt increase of the charge-density fluctuations just in the $n_c/4$ region. Therefore the increase of the fluctuations can be regarded as a manifestation of two-plasmon parametric instability that leads to formation of a high-power field of Langmuir waves in this region. This is also confirmed by the fact that the emission observed upon probing of the plasma at both $3\omega_0/2$ (Stokes) and $5\omega_0/2$ (anti-Stokes) have double-hump spectrum with a "blue" peak that is always less intense than the "red" one. Such a shape of the spectrum of the observed emission agrees with the theoretical notions concerning two-plasmon decay instability, according to which the transverse pump wave decays into two plasmons (blue and red) with frequencies shifted somewhat in both directions relative to $\omega_0/2$. Scattering of the probing wave by these plasmons should yield a double-hump spectrum in both the $3\omega_0/2$ and $5\omega_0/2$ regions. The distance $\delta\lambda_{3/2}$ between the peaks in the emission spectrum near $3\omega_0/2$ should be (in the wavelength scale) 1.6 times larger than the corresponding distance for the emission near $5\omega_0/2$; this is in satisfactory agreement with the experimentally observed ration $\delta\lambda_{3/2}/\delta\lambda_{5/2} \approx 1{,}9$.

Measurement of the relative intensities of the recorded emissions that are the result of Raman scattering of the heating and probing emissions allows us, as already noted to con-

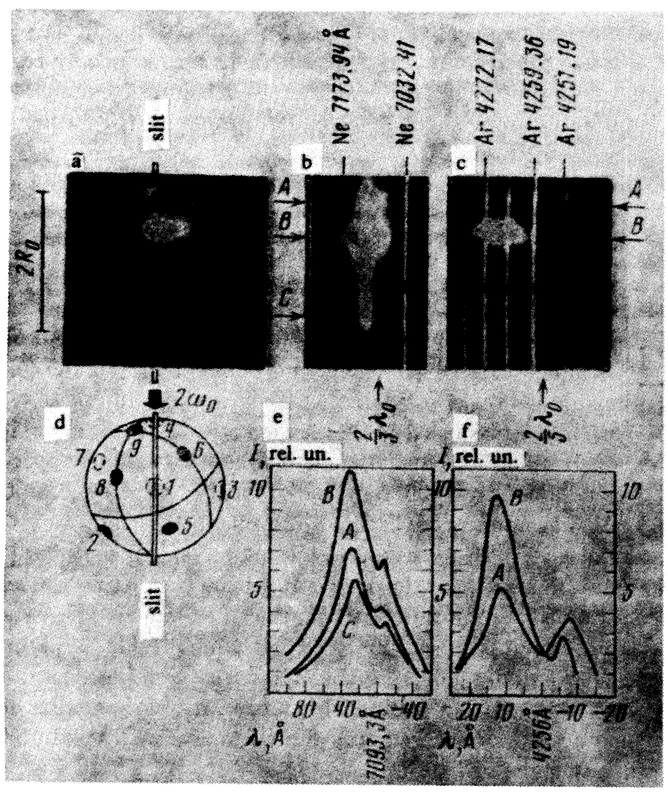

FIG. 3. a) Photograph of the glow of the plasma corona in the emission near $3\omega_0/2$. Spectrogram and spectral distributions of the plasma emission near $3\omega_0/2$ (b, e) and $5\omega_0/2$ (c, f). Arrangement of the spectrograph slits relative to the target image (d) (the numbers designate the optical axes of the laser beams; the probing emission is marked by an arrow). Target—hollow microsphere of $(C_8D_8)_n$ ($2R_0 \approx 217.8\ \mu$m, $\Delta_0 \approx 2.1\ \mu$m).

struct the turbulence spectrum for the conditions of the experiments in Refs. 16 and 17. In fact, in the formation of emission at $3\omega_0/2$ by scattering of a probing wave ($t^{pr}_{2\omega 0} + l_{\omega 0/2} \to t_{3/2\omega 0}$) at a scattering angle $\theta_s \approx 75°$, the Langmuir waves that take part have $k_l \approx 2{,}09\omega_0/c$, whereas at the frequency $^5/_2\omega_0$ ($t^{pr}_{2\omega 0} + l_{\omega 0/2} \to t_{5/2\omega 0}$ they have $k_l \approx 2{,}7\omega_0/c$. In the generation of the $3\omega_0/2$ harmonic by Raman scattering of the heating emission ($t_{\omega 0} + l_{\omega 0/2} \to t_{3/2\omega 0}$) the Langmuir waves involved have $0{,}55\omega_0/c \leqslant k_l \leqslant 2{,}13\omega_0/c$. These values of k_l are obtained from the momentum conservation law (e.g., $\mathbf{k}_l = \mathbf{k}_{5/2} - \mathbf{k}_2$ for $5\omega_0/2$), if the wave numbers of the transverse electromagnetic waves

$$k_{5/2}=\sqrt{6}\omega_0/c,\ k_2=(\sqrt{15}/2)\,\omega_0/c,\ k_{3/2}=\sqrt{2}\omega_0/c,\ k_0=(\sqrt{3}/2)\,\omega_0/c$$

are known (they are determined from the dispersion relations in the $n_c/4$ region). The large range of variation of k_l when the $3\omega_0/2$ harmonic is generated by the heating emission is due to the fact that under the conditions of Refs. 16 and 17 it is impossible to determine from experiment which of the laser beams gave the larger contribution to the recorded emission intensity of the harmonic. This means that the scattering angle of the heating emission is not determined but is located in the range $\theta_s \approx 0 - 137{,}5°$. On the contrary, the uncertainty in the values of the wave numbers of the plasmons that scatter the probing wave and produce the emissions at the frequencies $3\omega_0/2$ and $5\omega_0/2$ in a given observation direction is connected only with the angular apertures of the probing and recording systems ($\approx 12°$), and is therefore quite small ($1{,}81\omega_0/c \leqslant k_l \leqslant 2{,}34\omega_0/c$ for the case $3\omega_0/2$ and $2{,}34\omega_0 \cdot c \leqslant k_l \leqslant 3{,}04\omega_0/c$ for $5\omega_0/2$).

We assume for simplicity that the turbulence spectrum is isotropic. Then, starting from (1) and using the measured relations between the emission intensities at $3\omega_0/2$ and $5\omega_0/2$ (for the spectrograms of Fig. 3) and the relations between the flux densities of the heating and probing emissions, we obtain

$$(0.1 \text{ to } 2.0)\, W_l\left(0.55\frac{\omega_0}{c} \text{ to } 2.13\frac{\omega_0}{c}\right) \approx 5\cdot 10^{-3} W_l\left(2.08\frac{\omega_0}{c}\right) \approx W_l\left(2.7\frac{\omega_0}{c}\right), \qquad (2)$$

i.e., we obtain three points in the turbulence spectrum (Fig. 4). Naturally, the large uncertainty in the values of the wave numbers of the plasmons that participate in the scattering of the heating emission with formation of the $3\omega_0/2$ harmonic leads, according to (1), to a large uncertainty in the value of W_l determined from the intensity of this harmonic.

In the next run of experiments[20] with the "Kal'mar" facility the scattering spectra of the probing and heating emissions were recorded with spatial resolution over the plasma corona simultaneously in two channels (D, E in Fig. 2). This made it possible to expand the investigated range of plasmon wave numbers in the $n_c/4$ region. Indeed, plasma waves with respective values $k_l = 3{,}13\omega_0/c$ and $k_l \approx 4{,}09\omega_0/c$ take part in the formation of emission at the Raman-scattering frequencies $3\omega_0/2$ and $5\omega_0/2$ of the probing wave in the recording direction E (Fig. 2) at a scattering angle $\theta_s \approx 137.5°$. The wave numbers of the plasmons that scatter the heating emission and produce the $3\omega_0/2$ harmonics in this recording direction are contained in the same range as for the channel D ($0{,}55\omega_0/c \leqslant k_l \leqslant 2{,}13\omega_0/c$). By measuring the relative intensities of the Raman-scattering lines of the probing and heating emissions in the $n_c/4$ region for both indicated observation directions and using Eq. (1) we obtain the values of $W_l(k_l)$ in a wider range of wave numbers, namely $k_l \approx (0{,}55 - 4{,}09)\omega_0/c$. Such a turbulence spectrum, obtained for one of the polystyrene shell targets, is shown in Fig. 5. Its feature is the abrupt decrease of $W_l(k_l)$ at $k_l r_{De} > 0{,}2$. This is obviously due to the Landau damping of the plasma waves, which is known to set in at plasmon phase velocities V_{ph} close to the electron thermal velocity V_{Te}. Since $V_\Phi \approx V_{Te}/k_l r_{De}$, this means that in the region $k_l r_{De} \sim 1$ the intensity of the plasma oscillations should decrease substantially, as in fact observed in the measured turbulence spectrum. The obtained distribution of the plasma-wave intensity over the spectrum shows also a decrease of $W_l(k_l)$ in the region $k_l r_{De} \leqslant 0{,}13$. Although in this region the value of $W(k)$ is highly uncertain for the reasons noted above, this decrease can nevertheless be attributed to the low effectiveness of exciting long-wave oscillation in a bounded plasma volume. Indeed, plasmons with $k_l r_{De} \approx 0{,}01$ have a wavelength $\lambda_l \approx 6.10^2 \cdot r_{De} \approx 6\ \mu m$ ($T_e \approx 0.5$ keV), which is comparable with the characteristic size of the inhomogeneity in the $n_c/4$ region.

The plasma emission brightness at the harmonic frequency $3\omega_0/2$, measured in Refs. 16 and 17, permits an esti-

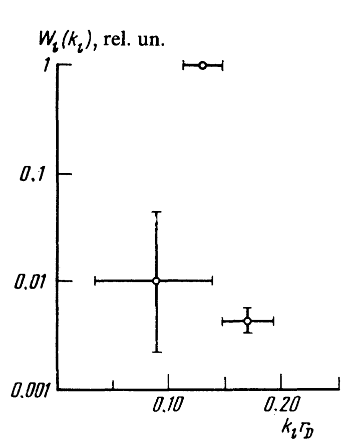

FIG. 4. Result of reconstruction of the plasma-turbulence spectrum in the $n_c/4$ region for the flash corresponding to Fig. 3.

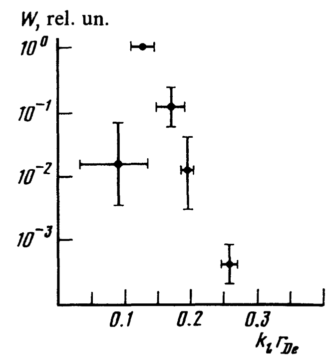

FIG. 5. Example of more complete reconstruction of the plasma-turbulence spectrum in the $n_c/4$ region when the scattering of the probing wave is recorded in two observation directions for one of the polystyrene targets.

mate of the total field intensity E_l of the Langmuir waves in the $n_c/4$ region. At the parameters of these experiments ($T_e \sim 0.5$ keV, $L \approx 30 - 30\ \mu$m) we obtain $E_l \approx 0.3E_0$. This estimate does not contradict the contemporary theoretical results and indicates that not more than 10% of the heating-emission energy is absorbed in the $n_c/4$ region on account of parametic instabilities.

3. SCATTERING OF PROBING EMISSION IN A REGION WITH CRITICAL DENSITY n_c

Laser plasma was investigated in the n_c region by the method of Raman scattering of the probing emission[18,19] in the "Kal'mar" facility simultaneously with the investigation of the $n_c/4$ region by the same method[16,17] as described above. The Raman frequencies of the scattering of probing emission of frequency $2\omega_0$ in the n_c region are the frequencies ω_0 and $3\omega_0$ shifted by $\Delta\omega = \omega_{Le}(n_c) = \omega_0$ relative to the probing-frequency $2\omega_0$. The spectrum of the scattered emission was recorded in the ultraviolet region (near the frequency $3\omega_0$) in the experiments of Refs. 18 and 19 at an angle 25° to the probing-beam axis (direction F, Fig. 2), corresponding to a scattering angle $\theta_s \approx 155°$.

Emission close to the frequency $3\omega_0$, with a two-component spectrum structure, was observed in the scattering spectrum of the probing wave in this registration direction when shell targets were irradiated. For the spectrogram of this emission, shown in Fig. 6a, both spectral components are shifted in the red direction relative to the exact value $\lambda_0/3 \approx 3546{,}7$ Å, the right one by 2.5 Å, and the broader and more intense left one by 18.5 Å. The width of the spectrum at the $I_{max}/2$ level is 15 Å (Fig. 6b). When the flux density of the heating emission was decreased to one-half the left-hand component of the spectrum vanished and only the right, weakly shifted component remained.

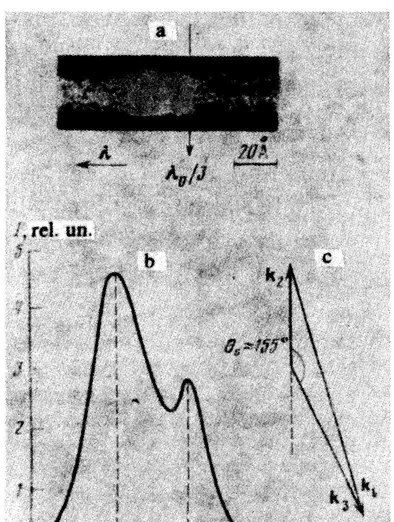

FIG. 6. Spectrogram and spectral distribution of the emission near the frequency $3\omega_0$ for a target of $(C_8D_8)n$ ($2R_0 \approx 196{,}8\ \mu$m, $\Delta_0 \approx 3.8\ \mu$m, $\lambda_0/3 \approx 3546{,}7$ Å), as well as diagram of the wave vectors.

In the absence of a probing wave, no emission was recorded near $3\omega_0$. This is natural at the employed heating emission flux densities. Indeed, the $3\omega_0$ harmonic can be produced in the plasma by four-wave coalescence of plasma waves and of a transverse pump wave in the n_c region ($3l_{\omega_0} \to t_{3\omega 0}, 2l_{\omega 0} + t_0 \to t_{3\omega 0}, 2t_0 + l_{\omega 0} \to t_{3\omega 0}$), processes of higher order than three-wave interaction. They are realized, however, at significantly higher flux densities.[21] The coalescence of the $2\omega_0$ harmonic generated in the plasma with the plasma oscillations ($t_{2\omega 0} + l_{\omega 0} \to t_{3\omega 0}$) has likewise low probability because of the low value of the coefficient of conversion ($\sim 10^{-7}$) of the laser radiation into the $2\omega_0$ harmonic in the plasma. It is furthermore clear that the probing emission itself cannot cause two-plasmon decay instability in its one-quarter critical density region (i.e., in the n_c region for the heating emission of a neodymium laser), since its flux density is lower by almost two orders than the threshold[22] for the development of this instability under the conditions of these experiments ($T_e \approx 0.5$ keV, $L \approx 30\ \mu$m). This means that the observed $3\omega_0$ emission is not the "one-and-one-half" harmonic of the probing wave.

The indicated features of the emission near the $3\omega_0$ frequency and the arguments advanced permit an unambiguous interpretation of this emission as the result of Raman scattering of the probing wave by the plasmons produced by the heating emission in the n_c region ($t^{pr}_{2\omega 0} + l_{\omega 0} \to t_{3\omega 0}$). We note that the probing wave is scattered in the plasma, generally speaking, in a wide range of electron densities $n_e \lesssim 4n_c \approx 4\cdot 19^{21}$ cm^{-3}. However, the appearance, in the scattering spectrum, of emission with frequency shifted relative to that of the probing wave by a value ω_0 equal to the electron Langmuir frequency ω_{Le} for the n_c region is evidence of an abrupt increase of the plasma-oscillation intensity in this region.

The presence of a threshold for the left-hand broader component of the emission spectrum near $3\omega_0$ suggests that it is due to scattering of the probing wave by plasmons excited as a result of parametric decay instability ($t_0 \to l + s$). The shift $\Delta\omega_3'$ of the spectrum of the broad component relative to $3\omega_0$ is determined here by the shift $\Delta\omega_l$ of the plasmon frequency relative to ω_0, the latter shift equal to the frequency of the ion-sound oscillations $\Delta\omega_3' = \Delta\omega_l = \omega_s(k_s) = v_s k_s$. Inasmuch as $k_s \approx k_l$ for the given parametric instability, we have $\Delta\omega_l \approx v_s k_l$. For the employed probing and recording geometry, the wave number of the plasmons that scatter the probing wave to produce the $3\omega_0$ emission is $k_l \approx 4.45\omega_0/c$. This value of k_l is obtained from the momentum conservation law for the Raman scattering $\mathbf{k}_l + \mathbf{k}_2 \to \mathbf{k}_3$ at the known values of the wave numbers of the transverse waves in the n_c region ($k_2 = \sqrt{3}\omega_0/c, k_3 = 2\sqrt{2}\omega_0/c$) and of the scattering angle $\theta_s \approx 155°$ (Fig. 6c). For the left-hand emission component near $3\omega_0$ we then obtain $\Delta\omega_3' \approx 4{,}45 v_s\omega_0/c \approx 2{,}6 v_s k_2$.

On the contrary, the small width and the small shift of the right-hand component of the $3\omega_0$ emission relative to $\lambda_0/3$ indicate that this component is due to scattering of the probing wave by plasma oscillations produced in linear transformation[9] of the transverse pump wave. The shift $\Delta\lambda_3''$ of this component can be attributed to the Doppler effect when the n_c scattering region moves with velocity u. This velocity can be determined from spectral measurements using the formula $\Delta\lambda_3''/\lambda_0 = {}^5/_9 u/c$, where c is the speed of light. According to this expression the red shift $\Delta\lambda_3'' \approx 2{,}5$ Å (Figs. 6a, b) corresponds to the velocity $u \approx 1{,}3\cdot 10^7$ of the n_c region towards the target center when the target is compressed by the laser pulse. This is in good agreement with the results obtained by other methods.[3,4,23]

It must be noted that the $2\omega_0$ harmonic generated under the conditions of the reported experiments[5] by the heating emission can also have a spectrum with two components, narrow and broad (~ 150 Å at the base; Fig. 7). The similarity of the shapes of the emission spectra near the frequency $3\omega_0$ and the harmonic $2\omega_0$ generated in the plasma[5] is due to the fact that these emissions are produced in the same n_c region by Raman scattering of the probing and heating emissions, respectively, by plasma waves of like nature. At the same time, the broad component of the $2\omega_0$ harmonic is produced at the densities employed mainly by coalescence of two plasmons ($l_{\omega 0} + l_{\omega 0} \to t_{\omega 20}$).[5] Their wave numbers are contained in a wide spectral band and can be large and close to the maximum k_m excited in ion-sound instability: $k_l k_m \gg k_2$. The estimated upper bound of the width $\delta\omega_2'$ of the spectrum of this harmonic is then given by

$$\delta\omega_2' \approx 2\Delta\omega_l = 2\omega_s = 2v_s k_s \approx 2v_s k_l \approx 2v_s k_m \gg 2v_s k_2.$$

This means that the width of this $2\omega_0$ component should exceed substantially the shift of the left-hand component of the emission near the frequency $3\omega_0$, as is observed in experiment.

To construct the spectrum of the plasma turbulence it is necessary to ensure as wide a range of scattering-plasmon wave numbers as possible. In experiments[16,17] devoted to the $n_c/4$ region (see the preceding section) this was accomplished by measuring the emission intensities of both Raman-scattering frequencies ($3\omega_0/2$ – Stokes and $5\omega_0/2$ – anti-Stokes) and of the $3\omega_0/2$ harmonic generated by Raman scattering of the heating emission. A similar approach to the investigation of the turbulene spectrum in the region of the critical density n_c, using the same probing emission with frequency $2\omega_0$, is difficult for the following reasons. The second (Stokes) Raman frequency of the scattering of the probing emission in the n_c region is ω_0, which coincides with the frequency of the heating light $t^{pr}_{2\omega 0} + l\omega_0 \to t\omega_0$ (the corresponding value of the wave number of the scattering plasmons is $k_l \approx 1{,}73\omega_0/c$ at any angle θ_s, inasmuch as $k_0 = 0$ in the n_c region). This coincidence makes it impossible to record this scattered radiation against the background of the much more intense pump wave reflected from the plasma even in the presence of spatial resolution. Measurement[5] of the intensity of the narrow spectral component of the $2\omega_0$ harmonic generated in the n_c region by Raman scattering of the heating wave (by plasmons with $k_l \approx 1{,}73\omega_0/c$ at any scattering angle) is possible only in the absence of probing emission, likewise because of the equality of their frequencies. To determine the plasma-oscillation energy distribution over the spectrum in the n_c region when using probing emission of frequency $2\omega_0$, the required range of k_l can be ensured only by varying the scattering angle θ_s and having several directions in which the emission near $3\omega_0$ can be recorded. If, however, another probing emission is used (e. g., with frequency somewhat different from $2\omega_0$), measurement, even in one observation direction, of the relative intensities of the Stokes and anti-Stokes components of the scattering of the probing wave and of the narrow component of the second harmonic makes it possible to determine directly three points in the spectral distribution of the plasma-wave energy in the n_c region. Recording these emissions in several directions leads to an even more complete reconstruction of the plasma-turbulence spectrum.

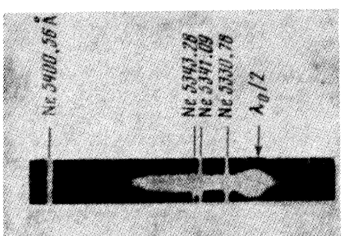

FIG. 7. Spectrogram of the emission of the $2\omega_0$ harmonic generated in the plasma by the action of the heating emission ($\lambda_0/2 = 5320$ Å).

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Translated by J. G. Adashko