Ultrahigh speed diagnostics of the parameters of laser plasma corona

V. Yu. Bychenkov, Yu. A. Zakhorenkov, O. N. Krokhin,
A. A. Rupasov, V. P. Silin, G. V. Sklizkov, A. N. Starodub,
V. T. Tikhonchuk, and A. S. Shikanov

P. N. Lebedev Physics Institute, USSR Academy of Sciences

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A method is proposed for the diagnostics of the local temperature and velocity of a laser plasma by determining the spectral characteristics of the harmonics of the heating radiation.

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The development of diagnostic methods with high temporal resolution is essential for the understanding of the physical processes that occur in the plasma corona of a target exposed to laser radiation. We discuss in this communication the possibility of determining the time evolution of the electron temperature and of the plasma velocity from the spectral lines of the harmonics of the heating-radiation frequency. We base ourselves on an experiment in which the time evolution of the spectrum of the harmonics $2\omega_0$ and $(3/2)\omega_0$, scattered by a laser plasma, was investigated. To heat the plasma we used two "Kal'mar" nine-channel neodymium-laser installation, whose radiation ($\lambda_0 \approx 10640$ Å, $\delta\lambda_0 \approx 10$ Å) was focused on the surface of solid and hollow-shell targets of SiO_2 or Al_2O_3. The radiation energy in the region of the target was $E \approx 100$–120 J at a flux density $q \approx 10^{14}$ W/cm^2.[1] The scattered radiation was investigated in the aperture of one of the focusing systems. The photorecorder operating in the slit-scanning regime with time resolution $\lesssim 0.1$ nsec received the incident radiation and the radiation scattered at frequency ω_0 through a three-step attenuator. Part of the scattered radiation was also diverted to the entry slit of an MDR-2 monochromator used as a spectrograph. The spectrally resolved radiation was transmitted through a light pipe to the photorecorder slit placed along the monochromator dispersion direction. The spectral resolution of the recording system was ≈ 1.5 Å for the $2\omega_0$ harmonic and ≈ 3 Å for $(3/2)\omega_0$. In the investigation of the $2\omega_0$ harmonic, radiation from a KDP, with wavelength corresponding to the exact value of $\lambda_0/2$ was used as a reference and was applied to the monochromator slit with a time delay. At the same time, two spectrographs (ISP-51) were used for integral spectral and spatial observation in the other directions.

A typical scan of the $2\omega_0$ spectrum is shown in Fig. 1. Just as in the integral measurements,[1] a

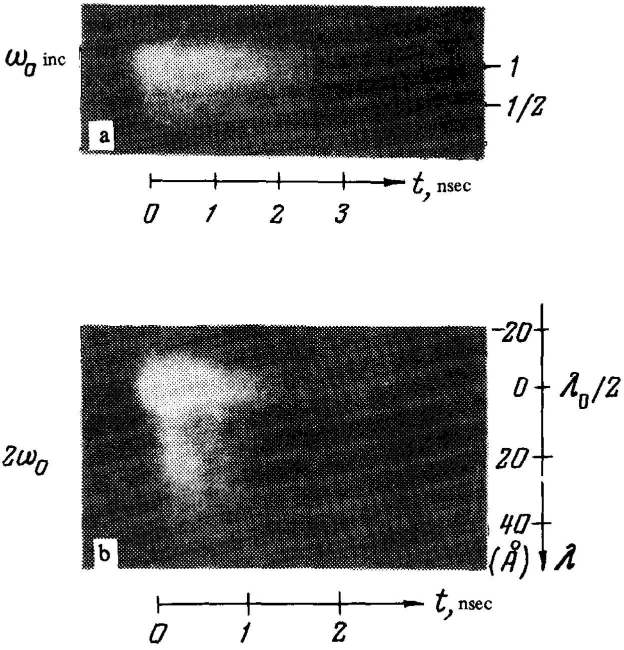

FIG. 1. Time scans: a—of the intensity of the heating radiation; b—of the spectral distribution of the $2\omega_0$ harmonic. Target—SiO_2 shell, $2R \approx 165$ μm, $\Delta R \approx 4$ μm.

complicated distribution is obtained, consisting of a fundamental component close to $\lambda_0/2$ and a pedestal shifted in the "red" direction and frequently taking the form of an additional component. The record shown in Fig. 1 reveals an increase of the fundamental component with time. The intensity of the fundamental component reaches the maximum at 0.5 nsec after its onset, the rise time of the heating radiation being ≈ 0.7 nsec, and decreases much more rapidly than the intensity of the heating radiation.

The emission of the additional component does not begin simultaneously, namely: the radiation with the larger wavelength appears later. At the instant when the maximum intensity of the fundamental component is reached ($t \approx 0.5$ nsec), the ratio of the intensities of the supplementary and fundamental components amounts to ≈ 0.1, and after 0.5 nsec ($t \approx 1$ nsec) it amounts to ≈ 0.35, i.e., the fundamental intensity component decreases more rapidly after reaching the maximum than the supplementary component. At the instant of time $t \approx 1$ nsec, the half-width of the fundamental $2\omega_0$ component (for Fig. 1) is ≈ 13 Å, and that of the total spectral distribution (at the level of 0.1 I_{max}) is ≈ 65 Å. The distance between the components is ≈ 22 Å.

The two-component $(3/2)\omega_0$ structure observed in the time-integrated investigation[2] takes place also in investigations with fine resolution (Fig. 2). The intensity ratio of the blue and red $(3/2)\omega_0$ components remains approximately constant (≈ 0.35 for Fig. 2), while the spectral distances between them at the instant corresponding to the three intensity maximum are 37, 44, and 33 Å, respectively. The half-width of the red component for the second and strongest peak is ≈ 44 Å, and that of the total integral distribution (at the $0.1 I_{max}$ level) is ≈ 120 Å. We note that even in a case when the heating pulse has a smooth intensity profile, modulation of the intensity of the scattered radiation is observed both at ω_0 and $(3/2)\omega_0$ (cf.[3]), with a period $\tau \approx 0.7$–0.8 nsec.

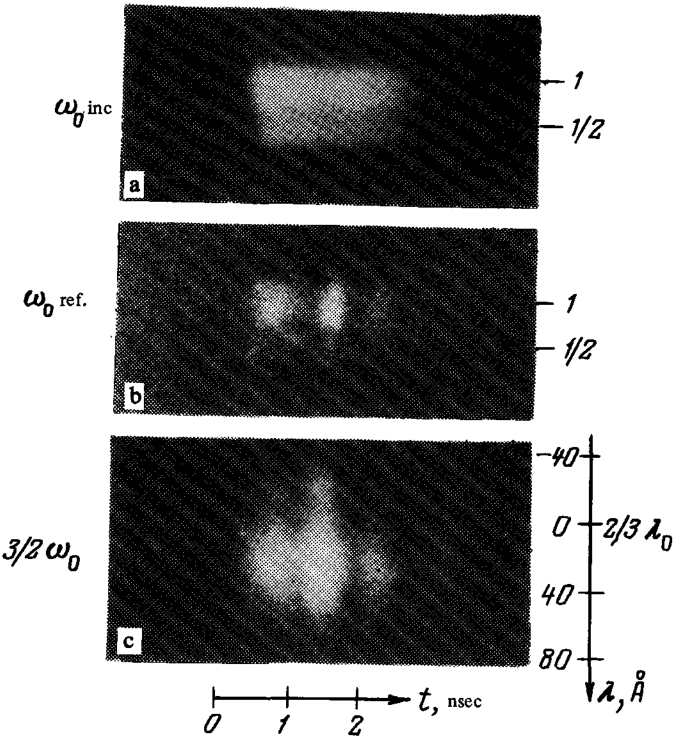

FIG. 2. Time scans: a—of the intensity of the heating radiation; b—of the intensity of the radiation scattered at frequency ω_0; c—of the spectral distribution of the $(3/2)\omega_0$ harmonic. Target—Al_2O_3 shell, $2R \approx 154$ μm, $\Delta R \approx 3$ μm.

The proposed method for the diagnostics of local plasma properties is based on the physical laws that govern the generation of the harmonics of the heating radiation. Attention must first be paid to the $2\omega_0$ harmonic, which can stem either from the p-component of the pump field because of the plasma inhomogeneity,[3,4] or from the development of paramagnetic turbulence.[5] The fundamental component of the $2\omega_0$ line can be attributed to p-component generation that leads to a narrow line of width $\delta\lambda_0$. The latter coincides with the experimentally observed broadening of the fundamental component.

The shift $\Delta\lambda_2$ of the maximum of the fundamental component of the $2\omega_0$ line is determined by the Doppler effect:

$$\Delta\lambda_2 = [u(t)/c]\lambda_0, \tag{1}$$

where $u(t)$ is the velocity of the plasma region in which the density is equal to the critical value, and c is the speed of light. Measurement of $\Delta\lambda_2$ therefore makes it possible to determine $u(t)$. According to (1), the shift of the fundamental component is towards the red side when the critical region moves towards the center of the target. Therefore the experimentally registered increase of the wavelength of the fundamental component is due to the increase of the velocity $u(t)$ in the course of contraction of the target, as observed in the experiments.[6] In particular, for the streak photographs shown in Fig. 1, the maximum value is $\Delta\lambda_2 \approx 2$ Å, which corresponds to a velocity $u \approx 6\times10^6$ cm/sec at $t \approx 1.5$ nsec.

The relatively broad pedestal of the $2\omega_0$ line can be understood on the basis of the concepts of parametric turbulence produced as a result of parametric decay or aperiodic instability. At the radiation fluxes used by us, the principal mechanism of nonlinear harmonic generation is the coalescence of two Langmuir waves. This coalescence leads to a large red shift of the $2\omega_0$ line, because spectral restructuring (say, decay-induced) enriches the spectrum of the Langmuir turbulence with the wavelengths $k^2 r_D^2/\omega_0 < \omega_0 - \omega_L$ (k is the wave vector, r_D is the Debye radius of the electrons, and ω_L is the electron Langmuir frequency). At the same time, the small blue shift of the second harmonic, due to coalescence of short-wave Langmuir waves $(k^2 r_D^2 \omega_0 > \omega_0 - \omega_L)$, provides weighty experimental proof of the presence of physical processes (for example, aperiodic instability) that lead to spectral transfer of the Langmuir turbulence into the region of shorter wavelengths. The overall second-harmonic pedestal broadening, which is determined by the spectrum of the Langmuir noise, amounts to

$$\delta\lambda_e \sim (k_{st} r_D)^2 \lambda_0 \tag{2}$$

(where k_{st} is the wave vector at which the Cerenkov damping of the plasma waves becomes substantial) and can reach values on the order of 100 Å under the conditions of our experiment, in agreement with the measurement results.

The physical causes of the two-component structure of the spectrum of the $(3/2)\omega_0$ harmonic were explained in[2]. This makes it possible by determining, from the distance between the blue and red components of $\Delta\lambda_{3/2}$, the electron temperature in the vicinity of one-quarter of the critical density, in accordance with the formula

$$T_e(t) \gtrsim 1.5\times10^{-2}\,\Delta\lambda_{3/2}(t), \tag{3}$$

where T_e is in keV and $\Delta\lambda_{3/2}$ is in Å. According to (3), at the instant of time corresponding to the maxima of the intensity of the $(3/2)\omega_0$ harmonic (Fig. 2), the temperature is 0.55, 0.65, and 0.5 keV, i.e., it changes by ≈30% during the time of the heating pulse.

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