Spectral and temporal measurements of radiation of light backscattered by a laser plasma

L. M. Gorbunov, Yu. S. Kas'yanov, V. V. Korobkin,
A. N. Polyanichev, and A. P. Shevel'ko

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

(Submitted 28 November 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 4, 242–246 (20 February 1978)

It is shown that the spectral-temporal characteristics of radiation backscattered by a laser plasma depend substantially on the density of the energy flux incident on the target. The results of the experiments are in qualitative agreement with the SMBS theory.

PACS numbers: 52.25.Ps, 52.50.Jm

An investigation of the spectral composition and of the intensity of the scattered radiation is one of the most promising methods of studying physical processes occurring in a laser plasma. Usually spectral measurements yield results averaged over the duration of the laser pulse. However, spectral-temporal measurements of the scattering near the laser-emission frequency, carried out in[1,2], have revealed noticeable variation of the spectrum during the pulse. We show in the present paper that the spectral characteristics of the radiation backscattered by the laser plasma not only vary with time, but depend substantially on the density of the energy flux incident on the target.

We used a single-frequency neodymium-glass laser of energy up to 30 J and pulse duration ~5 nsec with a rise time 0.8 nsec and a radiation contrast $\sim 10^{-5}$ at maximum input energy. The radiation was focused with a spherical lens ($f=300$ mm; $D=50$ mm) on the surface of a flat target of polyethylene or aluminum in vacuum. The diameter of the focal spot was monitored during each shot and amounted to ~30 μm, and the flux density on the target ranged from 3×10^{12} to 6×10^{14} W/cm^2. We used in the experiments a diffraction-grating monochromator (dispersion 12.5 Å/mm) and an electron-optical converter of the UMI-92 type. The spectral and temporal resolutions were ~0.2 Å and 5×10^{-11} sec, respectively.

Figure 1 shows four spectrograms of the radiation backscattered into the lens at different energy fluxes on the polyethylene target. At $P=5\times 10^{12}$W/cm^2 (Fig. 1b) the spectrum changes little with time, the line is broadened (~5 Å), and its center is shifted towards the red (~2 Å). With increasing flux, up to $P_1\sim(2\text{–}3)\times 10^{13}$ W/cm^2, the form of the spectrum remains in principle unchanged, although the line is broadened to 8–10 Å. When P_1 is exceeded, a blue part appears in the spectrum (Fig. 1c) and its width increases with increasing flux (Fig. 1d). The appearance of the blue component is delayed in time relative to the red component. This delay decreases with increasing flux and at $P\sim(3\text{–}5)\times 10^{14}$ W/cm^2 both parts of the spectrum occur practically simultaneously. In contrast to the blue component of the spectrum, the width of the red component changes little with increasing flux, and its center hardly shifts.

At fluxes exceeding 10^{14} W/cm^2, temporal oscillations are observed in the intensi-

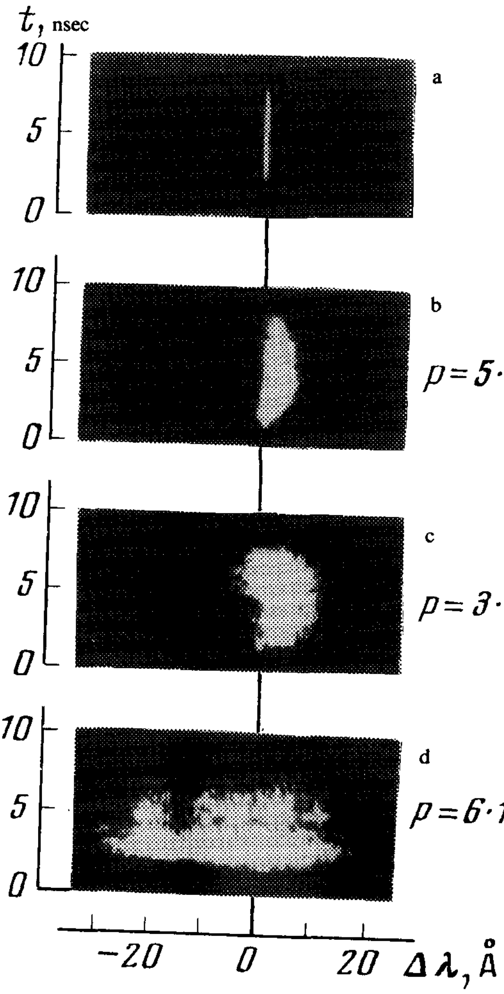

FIG. 1. Temporal spectrograms of laser pulses (a) and of scattered light (b, c, d) at various fluxes P.

ty of the scattered radiation, and are particularly clearly seen in the blue part of the spectrum (Fig. 1d). The characteristic period of the oscillations is ~0.7 nsec.

It follows from calorimetric measurements that the fraction of the energy scattered into the aperture of the focusing lens increases with increasing flux, from 1% at $P=3\times10^{12}$ W/cm² to 5% at $P=6\times10^{14}$ W/cm² for a polyethylene target. Owing to the strong modulation of the reflected radiation in time, the peak value of the reflection coefficient is much larger than 5%.

In addition, at $P\gtrsim10^{14}$ W/cm² the spectrograms reveal clearly a fine structure with a distance 1–2 Å between lines. Figure 2 shows by way of example the spectrum of the scattered radiation at a definite instant of time at $P=3\times10^{14}$ W/cm².

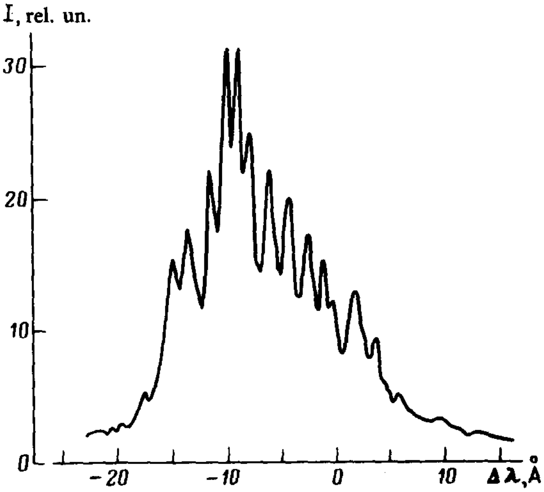

FIG. 2. Spectrum of scattered radiation at 3 nsec.

Polarization measurements have shown that in the blue part of the spectrum the scattered radiation has the same polarization as the incident laser light (the laser radiation is linearly polarized; the degree of depolarization is $\sim 10^{-2}$). In the red part of the spectrum, the light is slightly depolarized $((E_{\perp}/E_{\parallel}) \approx 3\text{–}4 \times 10^{-2})$.

The results of measurements with aluminum targets hardly differ from those with polyethylene.

The main characteristics of the spectrum of the scattered radiation can be understood on the basis of the theory of stimulated Mandel'shtam–Brillouin scattering (SMBS). According to this theory, the scattered wavelength λ differs from the wavelength λ_0 incident on the plasma by an amount (see, e.g., [3])

$$\Delta\lambda = \lambda' - \lambda_0 = 2\frac{\lambda_0}{c}(s - u)\sqrt{1 - (N/N_c)},$$

where $s = \sqrt{zT_e/m_i}$ is the speed of sound, u is the plasma flow velocity, z and m_i are the charge number and mass of the ions, T_e is the electron temperature, N is the electron density, and N_c is the critical density. In a laser plasma, the quantities that determine the hydrodynamics of the corona (T_e, u, N) are functions of the coordinates and of the time. Therefore different regions of the plasma corona produce scattered waves with different lengths. Figure 3 shows the dependence of $\Delta\lambda$ on the coordinate at $T_e = \text{const}$, $u \sim r$ and $N \sim r^{-3}$ (r_c is the coordinate at which $N = N_c$). It is seen that in the region of subsonic plasma flow we have $\Delta\lambda > 0$ and the scattered waves produced here determine the red part of the spectrum. The supersonic flow ($\Delta\lambda < 0$) is the cause of the blue part of the spectrum.

The distribution of the intensity of the scattered radiation over the spectrum depends on the plasma density profile. If the corona has small dimensions (small fluxes to the target), then the principal scattering is due to subsonic flow and only the red part is observed in the spectrum. With increasing flow, the dimension of the corona increases and a sufficiently dense plasma appears in the region of the supersonic flow. This gives rise to the blue component of the spectrum.

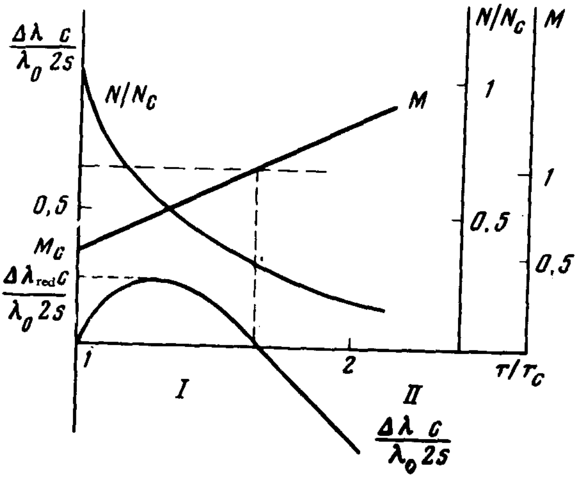

FIG. 3. Dependence of the shift of the scattered wavelength on the coordinate, and also on the plasma concentration and on the Mach number ($M=u/s$) in the corona. Regions I and II correspond to the red and blue parts of the spectrum.

The observed relatively weak broadening of the spectrum on the red side with increasing flux can be attributed to the presence of a maximum value of $\Delta\lambda_{red}$. For the functions N and u shown in Fig. 3, this value is given by

$$(\Delta\lambda_{red}/\lambda_0)(c/2s) \approx 2(1 - M_c)^{3/2}/3\sqrt{M_c},$$

where $M_c=u_c/s$ is the Mach number at the point r_c. At $T_e=600$ eV for polyethylene ($s=3\times10^7$ cm/sec) and $\Delta\lambda_{red}=4.5$ Å we obtain $M_c=0.6$.

Using the known expressions[4] for the gain in SMBS in an inhomogeneous plasma, we can obtain the intensity of the radiation scattered by different sections of the plasma and calculate the spectrum. For the simplest hydrodynamic models such a calculation leads to satisfactory agreement with the experimental results.

The modulation observed in the spectrum and the fact that the intensity oscillates with time indicate that the reflected-radiation spectrum is influenced by other processes in addition to SMBS.

In conclusion, the authors are deeply grateful to P. P. Pashinin for interest in the work.

[1] B. H. Ripin, I. M. McMehon, E. A. McLean, W. M. Manheimer, and I. A. Stemper, Phys. Rev. Lett. 33, 634 (1974).
[2] E. Jennitti, A. NaMalvezzi, and G. Tondello, J. Appl. Phys. 46, 3096 (1975).
B. Grek, H. Pepir, and F. Rhesult, Phys. Rev. Lett. 38, 898 (1977).
C. S. Lin, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).