DETERMINATION OF THE PARAMETERS OF A DENSE PLASMA FROM THE SHIFT AND HALF-WIDTH OF THE SATELLITES OF THE SCATTERED-LIGHT SPECTRUM

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Abstract

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DETERMINATION OF THE PARAMETERS OF A DENSE PLASMA FROM THE SHIFT AND HALF-WIDTH OF THE SATELLITES OF THE SCATTERED-LIGHT SPECTRUM

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Determination of plasma parameters from the scattering of laser radiation by electrons is based on analysis of the spectrum of the scattered light.

The scattering cross section of polarized light by plasma electrons at an angle θ has the form ([1−3])

$$\sigma = \frac{e^4}{m^2c^4}\frac{1}{\sqrt{\pi}}\Gamma_\alpha(x)\frac{1}{\omega_e}, \tag{1}$$

where e, m are the charge and mass of the electron; $x = \Delta\omega/\omega_e$ is the dimensionless frequency;

$\Delta\omega = \omega - \omega_0$; ω_0 is the frequency of the probing radiation; $\omega_e = \frac{4\pi\sin(\theta/2)}{\lambda}\sqrt{\frac{2kT_e}{m}}$;

$\alpha = \sqrt{\frac{n_e e^2}{4\pi kT_e}}$; n_e, T_e are the concentration and temperature of the electrons;

λ is the wavelength of light, k is Boltzmann' s constant.

The scattering spectrum is determined by the function $\Gamma_\alpha(x)$ ([1]), and its character by the parameter α. A low-temperature dense plasma, as a rule, corresponds to the case $\alpha > 1$, when collective effects begin to appear and two satellites arise in the spectrum, symmetric with respect to the laser line.

In this case the spectral intensity of the scattered light over the entire frequency range, except for the frequencies corresponding to the positions of the satellites, is at the level of plasma noise. Therefore, when satellites are present it is impossible to determine the plasma parameters from the integral intensity of the scattered light, as is done for $\alpha \ll 1$. However, under the indicated conditions it becomes possible to calculate the plasma parameters from other characteristics of the spectrum: from the shift of the satellites $\Delta\omega_1$ and from its half-width $\delta\omega$.

For $\alpha \gg 1,\ x_1 \gg 1$, the function $\Gamma_\alpha(x)$ can be simplified ([1]) by writing it in an approximate form, which makes it possible to obtain relations for interpreting the spectrum in analytic form

$$\delta\omega/\Delta\omega_1 = \delta x/x_1 = \sqrt{\pi}/2\alpha^3 e^{-\alpha^2/2}; \tag{2}$$

$$n_e = \frac{1}{4\pi}\frac{m}{e^2}(\Delta\omega_1)^2; \tag{3}$$

$$T_e = \frac{m\lambda^2}{16\pi^2 k \sin^2(\theta/2)}\left(\frac{\Delta\omega_1}{\alpha}\right)^2. \tag{4}$$

In connection, however, with the fact that the solutions obtained are valid for $\alpha \gg 1,\ x_1 \gg 1$ and the accuracy of interpreting the spectrum by formulas (2)–(4) proves insufficient for conditions $\alpha \sim 1$, it becomes necessary to determine the plasma parameters with allowance for the complete expression for $\Gamma_\alpha(x)$. Since $\Gamma_\alpha(x)$ is a complex function, the most convenient method of solution is graphical.

By determining $x_1 = \Delta\omega/\omega_e$ and $\delta x = \delta\omega/\omega_e$. Since ω_e depends only on $\omega_0,\ T_e$, and θ, which for a given experiment remain unchanged, then with ⋯

using $\Gamma_\alpha(x)$ one can obtain the dependence

$$\delta\omega/\Delta\omega_1 = \delta x/x_1 = \varphi(\alpha), \tag{5}$$

which makes it possible to determine α from the characteristics of the spectrum. In an analogous way one can construct the function

$$x_1 = \chi(\alpha). \tag{6}$$

From (6), for a known α, x_1 is found.
But $\omega_e = \Delta\omega_1/x_1$, whence

$$T_e = \frac{m\lambda_0^2}{32\pi^2 k \sin^2(\theta/2)}\left(\frac{\Delta\omega_1}{x_1}\right)^2. \tag{7}$$

From (7) and the expression for α, n_e is found:

Fig. 1. Dependences $\delta x/x_1$ (1) and x_1 (2) on α.

Figure 1: Fig. 1. Dependences $\delta x/x_1$ (1) and x_1 (2) on α.

$$n_e = \frac{1}{8\pi}\frac{m}{e^2}\left(\frac{\alpha}{x_1}\right)^2 \Delta\omega_1. \quad (8)$$

The dependences $\varphi(\alpha)$ and $\chi(\alpha)$ are shown in Fig. 1.

Fig. 1. Dependences $\delta x/x_1$ (1) and x_1 (2) on α.

To obtain the scattering spectrum, experiments were carried out with the plasma of an argon arc at atmospheric pressure. The arc current was 14 A. Most of the results were obtained with tungsten electrodes ([4]). An arc with carbon electrodes was also used.

Usually the scattering method is applied for diagnostics of a fully ionized plasma. The plasma of an arc at atmospheric pressure is characterized by the presence of a large number of neutral atoms (degree of ionization of order 0.1). In this connection, in addition to the usual difficulties of the method, there are added difficulties caused by the high level of Rayleigh scattering, plasma noise—especially near emission lines—and the presence of solid particles. The features of the experimental setup that make it possible to overcome these difficulties are described in ([4]).

Figure 2 shows oscillograms of the scattering signal. Oscillogram 2a was obtained at a wavelength of 6891 Å (tungsten electrodes). In this spectral range the background of the setup was not recorded because of its smallness. The large peak on the sweep is due to scattering by electrons; the small peaks are plasma noise. From the oscillogram it is seen that the plasma background is several times smaller than the scattering signal. This made it possible to construct the electron-scattering spectrum, which is shown in Fig. 3.

In Fig. 3 the abscissa gives the absolute values of the wavelengths, and the ordinate gives the relative intensities of the signals (the ratio of the signal amplitude to the amplitude at the wavelength of the laser radiation).

The dependence on wavelength of the intensity of light scattered by details of the apparatus (the apparatus background) and of Rayleigh scattering in cold argon on wavelength is shown in Fig. 3 by a dashed line. It was obtained in argon under the same conditions as the signal from scattering by the plasma, but with the plasma switched off. As follows from the graph, the apparatus background is significant only in the spectral interval 6943 ± 8 Å. Outside this interval the density of the background spectrum is small, and at a distance of ± 10 Å from the laser line it may be neglected.

The curve drawn through the black points describes the spectrum of light scattered by the plasma at a probing-radiation power of 10 MW. The spectrum

Fig. 2. Scattering oscillograms.

Figure 2: Fig. 2. Scattering oscillograms.

has a center of symmetry located at the wavelength of the laser radiation, and two symmetric satellites. The central maximum of high intensity is due to light scattering from parts of the apparatus, solid particles, Rayleigh scattering, and scattering by plasma ions. The satellites are associated with the scattering of light by free electrons of the plasma.

Fig. 2. Scattering oscillograms. *a*—scattering by plasma, tungsten electrodes, $\lambda = 6891$ Å; *b*—scattering by plasma, carbon electrodes, $\lambda = 6923$ Å; *c*—background of the apparatus, $\lambda = 6923$ Å

The curves drawn through the bright points correspond to a probing-radiation power of 6 MW. The satellites of the second series essentially repeat the character of the behavior of the first curve.

Consequently, the probing radiation does not affect the plasma parameters, or, in any case, this influence is small.

As can be seen from Fig. 3, the satellite shift $\Delta\omega_1$ is 50 Å and is determined with high accuracy. The accuracy of determining the half-width $\delta\omega$ is considerably lower. It may be assumed that $\delta\omega$ is 14–20 Å.

The data obtained were used to calculate the plasma parameters by the formulas of the first approximation and of the exact solution for $\Delta\lambda_1 =$

Table 1

	$\Delta\lambda$, Å	$\delta\lambda$, Å	n_e, cm^{-3}	T, °K	α
First approximation	50	20	$1.2 \cdot 10^{17}$	18 000	3.0
First approximation	50	14	$1.2 \cdot 10^{17}$	16 000	3.2
Exact solution	50	20	$5.9 \cdot 10^{16}$	23 000	1.8
Exact solution	50	14	$7.2 \cdot 10^{16}$	16 500	2.4

$= 50$ Å, $\delta\lambda = 14$ Å and $\delta\lambda = 20$ Å. The results of the calculations obtained are presented in Table 1. As can be seen from the table, the results of processing the material by the exact solution differ noticeably from the approximate one; n_e, which depends mainly on the position of the satellite, is determined with good accuracy. T_e, which depends on the half-width of the satellite, is determined less

Fig. 3. Spectrum of light scattering in plasma

Figure 3: Fig. 3. Spectrum of light scattering in plasma

accurately. Let us note that, according to (5), in our case (the observation angle of the scattered light is $\Omega = 0.34$ sterad), when calculating the temperature at $\alpha = 2.4$ one should take into account the finiteness of the observation aperture.

Fig. 3. Spectrum of light scattering in plasma

In Figs. 2 and 2 oscillograms of experiments on plasma with carbon electrodes are presented. Photograph 2 corresponds to the case of scattering by plasma at the wavelength 6923 Å. Photograph 2 shows the signal from the background of the setup at the same wavelength in the absence of plasma. Since the background of the setup is not zero, scattering by electrons corresponds to the difference of the signals. The scattering spectrum in a carbon arc with the indicated parameters has two weakly expressed satellites, which corresponds to $\alpha \sim 1$. The maxima of the satellites are located symmetrically with respect to the laser line at a distance of ± 20 Å. In this case, for estimating the plasma parameters one may use the inequality $\alpha \gtrsim 1$, since satellites exist only for $\alpha > 1$. Since their presence was established, then, taking this condition into account,

$$n_e = 9.0 \cdot 10^{15}\ \text{cm}^{-3}, \qquad T_e \lesssim 10\,000^\circ\ \text{K}.$$

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Note: Figure translations are in progress. See original paper for figures.