THOMSON SCATTERING OF RUBY LASER LIGHT BY PLASMA BEHIND COLLISIONLESS SHOCK WAVE FRONT

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Recording of laser radiation scattered by a plasma is essentially the only method which makes it possible to determine the local values of the temperature and density without disturbing the plasma. At the present time the Thomson scattering method permits measurements [1-3] of the plasma parameters in the region $10^{12} \leqslant n_e \leqslant 10^{17}$ cm^{-3}. We note that when using laser sparks the upper limit of the determination of $n_e > 10^{19}$ cm^{-3} (for example, [4]). However, in the region of low concentrations only specimens with slowly varying parameters have been investigated [1, 2]. One interesting region of application of this method is the shock waves in a rarefied plasma, which are accompanied by rapid variations of the parameters of the medium and effective heating of the plasma [5, 6]. Here the principal interest is in the question of which of the components – electron or ion – experiences the predominant heating, since the nature of the heating is intimately connected with the nature of the microprocesses within the shock transition and the front macrostructure [7]. Measurements using magnetic probes, based on plasma electron diamagnetism [8], showed that there is a critical value H_* of the wave amplitude, below which ($H < H_*$) in the wave the electrons are predominantly heated and when this critical value is exceeded ($H > H_*$) the electron pressure fraction in the overall plasma pressure falls off rapidly, which it is natural to explain by increase of ion heating. It is important to show by an independent method that the results in the supercritical region ($H > H_*$) are not connected with the disturbing effect of the probes or limitations of the experimental technique. The present experiment was conducted with this objective.

It is known [9] that the nature of the scattered signal spectrum depends on the parameter α, which defines the relation between the wavelength λ, the Debye radius r_D, and the scattering angle θ

$$\alpha = \frac{\lambda}{4\pi r_D \sin {}^1\!/_2\,\theta} \tag{1}$$

We see from (1) that in the region of low concentrations and high electron temperatures it is quite difficult to realize the collective scattering condition ($\alpha > 1$). Thus, for the observation angle $\theta = 90°$ selected in the described experiment the case $\alpha \ll 1$ is realized, i.e., Thomson scattering by free electrons.

For a Maxwellian electron velocity distribution the profile of the Thomson scattering line has a Gaussian shape with halfwidth

$$\Delta\lambda = 4\sqrt{2\ln 2}\,\frac{\lambda}{C}\left(\frac{kT_e}{m}\right)^{1/2}\sin\frac{\theta}{2} \tag{2}$$

For $\lambda = 6943$ Å and $\theta = 90°$ this relation takes the form

$$\Delta\lambda\,[\text{Å}] = 32.4\sqrt{T_e}\,[\text{eV}] \tag{3}$$

The basic experiments were conducted on a UN-4 setup [5-7]. The hydrogen preplasma with density $n_e \approx 2 \cdot 10^{14}$ cm^{-3} and initial temperature 1-5 eV was created in the cylindrical volume 4 (glass tube of radius R = 8 cm) mounted in a quasistationary magnetic field $H_0 = 400$ Oe (Fig. 1). The shock wave was generated by the "magnetic piston" ($H_\sim = 2.5$ kOe) as the rapidly rising current passed through the coil 5.

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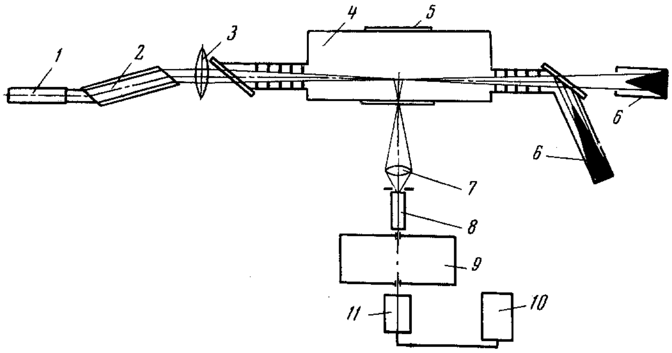

Fig. 1

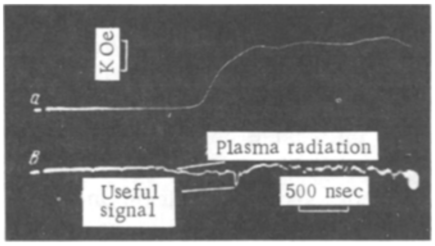

Fig. 2

The magnetic field jump in the wave was measured by a magnetic probe located at the midsection of the shock coil at $r = \frac{1}{2} R$. The maximal field intensity $H = H_0 + H_\sim$ in the wave in these experiments exceeded the critical value $H_* \approx 3.5\, H_0$.

The laser system consisted of the ruby generator 1 ($d = 11$ mm, $l = 120$ mm), controlled by a quaterwave nitrobenzene Kerr cell, and the amplifier stage 2, whose active element was a ruby with sapphire ends cut at the Brewster angle. The energy and duration of the giant pulse of this system were respectively $Q = 1$-4 J, $\tau = 10$-15 nsec.

The laser light was focussed by the lens 3 (Fig. 1) through the glass window, mounted at the Brewster angle, at the midsection of the shock coil. After passing through the volume 4 and a system of diaphragms, the straight beam was led out through a glass window, also mounted at the Brewster angle. The light exiting into the atmosphere and also the light reflected from the exit window was adsorbed by the traps 6. The laser radiation scattered by the plasma electrons was let out through a small glass window in the central part of the shock coil and was gathered by the lens 7 on a collimating slit located at the entrance of the fiber-optics lightguide 8, which transmitted the image to the slit (width 0.5 mm) of the MDR-2 diffraction monochromator 9 with linear dispersion 40 Å/mm and geometric aperture ratio 1 : 2.5. The photomultiplier FÉU-52 was located behind the monochromator exit slit. This photomultiplier 11 was carefully screened against interference. The signal from the photomultiplier traveled through an amplifier (gain 2-100, $\Delta f = 10^8$ Hz) to the DÉSO-1 oscillograph 10.

The plasma self-radiation was commensurate with the scattering signal, therefore the authors had to give up the multichannel recording system [3]. For this reason the entire spectrum of the scattered radiation was recorded by realigning the monochromator with respect to the wavelength after about 100 cycles of operation of the entire system with careful monitoring of the setup operating regime. The stability of the laser power was monitored by a coaxial photocell. The initial plasma parameters and the magnetic field profile in the shock wave were recorded in each experiment (Fig. 2a). Only that portion of the frame was analyzed in which the reproducibility of the initial plasma parameters and the amplitude wave was within 10-20%.

The shock wave excitation and laser triggering were synchronized so that the stimulated radiation occurred at the moment the shock wave crest reached the region where the laser beam was focused (Fig. 2). Therefore the scattering spectrum was determined by the electron temperature behind the wave front. Figure 2b shows the light signal scattered by the plasma on the background of its self-radiation (at a distance 100 Å from the spectrum center $\lambda_0 = 6943$ Å).

Unfortunately the geometry of the experimental setup did not permit installing a light trap opposite the recording system, therefore the background level owing to scattering of the laser radiation by the chamber walls exceeded the useful signal by a factor of 3-4 at the center of the profile. However, the parasitic signal was observed only in a narrow interval $\delta\lambda = 20$-30 Å and was completely absent in the profile "wings" even at maximal sensitivity of the entire recording system. Thus, with a Thomson profile halfwidth $\Delta\lambda$ of order 200-300 Å the narrow interval $\delta\lambda$ with high parasitic background level can be discarded without having any significant effect on the accuracy of the temperature determination. The true

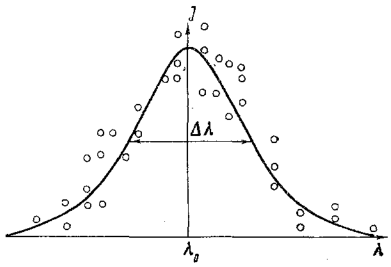

Fig. 3

signal of the radiation scattered by the plasma electrons was determined by subtracting the interference owing to plasma self-radiation from the overall signal. Under typical experimental conditions the useful signal exceeded the plasma background by about 2.5 times (Fig. 2) at a distance 100 Å from the center of the line $\lambda_0 = 6943$ Å.

The experimental dependence $J(\lambda)$ of the scattered laser radiation intensity is shown in Fig. 3. The experimental points fall well on the Gaussian curve, which indicates sufficient thermalization of the plasma electron component. In accordance with (3) the experimentally determined profile width $\Delta\lambda = 250$ Å corresponds to the electron temperature $T_e \approx 60$ eV. The average value of T_e in this same range measured by the probe method [8] amounts to about 50 eV. The quite satisfactory agreement of these values confirms the correctness of the probe measurements made previously.

In spite of the considerable increase (by more than an order) of the electron temperature in the wave front, it remains several times smaller than the value obtained in the numerical solution of the problem on a computer [8] under the assumption that wave energy dissipation takes place only as a result of Joule heating of the electrons. This deviation is observed only for $H > H_*$, therefore it is natural to assume that in the supercritical region the model with purely electron heating is invalid, i.e., in the real experiment there is significant heating of the ions, which agrees with recent energy measurements of the plasma ion component [10].

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