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MEASUREMENT OF ELECTRIC FIELDS IN TURBULENT PLASMA FROM THE STARK BROADENING OF HYDROGEN SPECTRAL LINES

I. In the dynamics of turbulent plasma, a determining role is played by electrostatic oscillations, which lead to an effective transfer of the energy of directed particle motion into heat (^{1}). Measurement of the electric-field strengths of such oscillations and of their energy density is one of the urgent problems of plasma physics. A good noncontact optical method for measuring electric fields developing in turbulent plasma may be the measurement of Stark broadening of the spectral lines of the hydrogen atom (^{2}, ^{3}). In the present work, this method was used to investigate electrostatic oscillations arising during turbulent heating of plasma by the current of a direct discharge.

According to theoretical concepts, the profile of a hydrogen spectral line emitted from turbulent plasma contains information not only about the field strength of the oscillations, but also about their frequency spectrum. Usually the period of ion-acoustic and still lower-frequency plasma oscillations proves to be substantially greater than the lifetime of the emitting atom on an individual Stark sublevel. Therefore the action of such low-frequency oscillations on the hydrogen atom is quasistatic (^{4}). If, in addition, the mean field strength E_{av} of the electrostatic oscillations substantially exceeds the Holtsmark field $E_H = 2.6\,eN^{2/3}$, then the half-widths of spectral lines that have no central Stark component $(L_{y-3}, H_\beta, H_\delta)$ will be related to E_{av} by the relation

$$\Delta\lambda_{1/2} = \frac{3}{8\pi c}\lambda^2(n^2 - n'^2)\frac{ea_0}{\hbar}\,\widetilde{E}_{\text{av}}. \tag{1}$$

Here λ is the wavelength of the line under consideration; n and n' are the principal quantum numbers of the upper and lower levels, the transition between which gives emission at this wavelength. In order that the inequality $\widetilde{E}_{\text{av}} \gg E_H$

Fig. 1. Photograph of the time sweep of the H_α line. Sweep duration 20 μsec.

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Fig. 2. Photograph of the time sweep of the H_β line. Sweep duration 20 μsec.

Figure 2: Fig. 2. Photograph of the time sweep of the H_β line. Sweep duration 20 μsec.

be fulfilled, the degree of turbulence (the ratio of the energy density in ion-acoustic oscillations w_i to the kinetic energy density of particles $N_{eT}e$) must exceed the value

$$(w_i/N_{eT}e)_{\text{cr}} \simeq E_H^2/8\pi NT \simeq e^2 N^{1/3}/\pi T_e. \qquad (2)$$

Under typical conditions of turbulent plasma heating by current, the degree of turbulence is $w_i/N_{eT}e \sim 10^{-2}$ at $N_e \simeq 2 \div 5 \cdot 10^{13}$ cm^{-3} and $N_{eT}e \sim 10^{16}$ eV $\cdot$ cm^{-3}. This means that the half-width of the H_β line emitted under these conditions should exceed by almost an order of magnitude its value for equilibrium plasma, and that a characteristic dip should exist at the center of the line. It is significant that lines with a strong central component, such as $L_{y-\alpha}$, H_α, H_γ, P_α, should not in this case undergo noticeable broadening, since the half-widths of their profiles are determined mainly by electron-impact broadening of the unshifted Stark component.

When turbulence develops in the plasma at Langmuir frequencies, the profiles of hydrogen spectral lines will behave differently. The frequency of Langmuir oscillations ω_{pe} substantially exceeds the precession frequency of the dipole moment of the hydrogen atom $\omega_E = \frac{3}{2} n \frac{a_0 e}{\hbar} E$ in an electric field.

···and therefore the action of such oscillations on the radiating atom proves to be essentially nonadiabatic. Like electron impacts, Langmuir oscillations cause transitions between Stark sublevels and determine the lifetime of the atom in the state with quantum numbers n_1, n_2, m. The half-width of a Stark component in a plasma with developed turbulence at Langmuir frequencies proves to be related to the degree of turbulence of these oscillations in the following way:

Fig. 1. Photograph of the time sweep of the H_α line. Sweep duration 20 μsec.

Fig. 2. Photograph of the time sweep of the H_β line. Sweep duration 20 μsec.

$$\Delta\lambda_{1/2} \simeq \frac{3\lambda^2 a_0}{m_e \omega_{pe} c} N_e T_e \left(\frac{w_e}{N_e T_e}\right) n^2 \left[n^2 - (n_1 - n_2)^2 - m^2 + 1\right]. \qquad (3)$$

Here

$$w_e = \int \frac{E_k}{8\pi}\, dk$$

Fig. 3. Spectrochronogram of the H_α line. Sweep duration 3 μs.

Figure 3: Fig. 3. Spectrochronogram of the H_α line. Sweep duration 3 μs.

is the energy density in the Langmuir oscillations; n_1, n_2, m are parabolic quantum numbers determining the state of the hydrogen atom in an electric field (^{5}). The development of turbulence at Langmuir frequencies will primarily affect the profile of lines with a strong central component ($L_{y-\alpha}, H_\alpha, H_\gamma, P_\alpha$).

II. The experiments were carried out on the NPR-2 device, which is a probotron with a mirror ratio equal to 2. The working volume was filled with plasma by means of two film-hydride injectors, to which a direct-discharge voltage was applied. A detailed description and diagram of the apparatus are given in (^{6}).

Light was extracted from the chamber at a distance of 30 cm from the anode of the direct discharge and analyzed by means of a Fabry–Perot interferometer coupled to an ISP-51 spectrograph. The thickness of the Fabry–Perot etalon spacer was 0.3 mm and provided a dispersion range $\Delta\lambda_s = 7.2$ Å at the wavelength of the H_α line and $\Delta\lambda_s = 3.93$ Å at the wavelength of the H_β line. Recording of the time sweep of the line contours was carried out by electron-optical spectrochronography, the effectiveness of which for measuring nonequilibrium electric fields from Stark broadening of lines in collisionless shock waves is shown in (^{7}). The image from the screen of the electron-optical converter was photographed on RF-3 film and then photometered on an MF-4 microphotometer. The instrumental half-width was 0.3 and 0.2 Å for the H_α and H_β lines, respectively.

III. Experiments on measuring the profiles of the H_α and H_β lines under turbulent heating of the plasma by current were carried out under the following conditions: the magnetic field at the center of the trap was $H = 5$ kOe, the voltage on the direct-discharge capacitor was $U = 30$ kV, $N_e = 2 \cdot 10^{13}$ cm^{-3}, $N_e T_e \sim 7 \cdot 10^{15}$ eV $\cdot$ cm^{-3} (the concentration was measured from the cutoff of a microwave signal with wavelength 8 mm). The direct-discharge voltage was applied to the injectors 8–12 μs after the latter were switched on. Under these conditions the degree of ionization of the plasma is $\sim 95\%$, and in the central part of the column, where ion-acoustic oscillations apparently are excited, atoms of neutral hydrogen are practically absent. All the light emission comes from the periphery of the plasma, where there are no substantial electric fields, as a result of which the observed line remains narrow.

Fig. 3. Spectrochronogram of the H_α line. Sweep duration 3 μs.

When neutral hydrogen is admitted into the chamber to a concentration $N_0 = 0.5 \div 0.10\, N_e$, the central regions of the plasma column, where intense electric microfields of the oscillations are present, should also participate in the emission. In this case a substantial broadening of the line profile is indeed observed.

Fig. 4. a—profile of two orders of the H_β line (division value along the λ axis 0.5 Å); b—profile of the H_α line

Figure 4: Fig. 4. a—profile of two orders of the H_β line (division value along the λ axis 0.5 Å); b—profile of the H_α line

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In Figs. 1 and 2 photographs are presented of the time sweep of two interference orders of the H_α and H_β lines, respectively. In these photographs one can see a sharp broadening of the lines, which lasts for $1 \div 1.5$ μs from the start of the direct discharge. The same effect is observed in Fig. 3, which shows a spectrochronogram of the H_α line on a fast sweep. In this case the broadening of the H_α line reaches a maximum in the first half-period of the current.

and vanishes at the moment when the current passes through zero. Unfortunately, the lack of light did not allow us to record the contour of the H_β line on a fast sweep, or to carry out a quantitative study of the time dependence of the broadening of the H_α line.

Figure 4 shows the contours of the H_β and H_α lines obtained by photometric processing of the spectrochronograms already described. The half-width of the H_β line is ~ 1.8 Å, and that of H_α is ~ 1 Å; moreover, the H_α line has clearly pronounced extended wings. This broadening of the lines cannot be caused by high-frequency (Langmuir) oscillations, since they cannot give half-width values greater than $\Delta\lambda_{1/2} = \lambda^2 \omega_{pe}/2\pi c$ (^{7}). In our experiments $\omega_{pe} \sim 2.5 \cdot 10^{11}$—$3 \cdot 10^{11}$, and, consequently, because of Langmuir oscillations the half-width of the H_β line cannot exceed 0.3 Å, and that of H_α, 0.5 Å. Nor can these same oscillations explain the appearance of wings in the H_α line. It is therefore clear that the broadening is caused by quasistatic (ion-acoustic) oscillations. The absence of the central dip in the H_β line (Fig. 4), characteristic of quasistatic fields, is due to the fact that in observation we average the radiation intensity over the entire transverse cross section of the plasma column, i.e., light from the outer regions of the plasma, where ion-acoustic oscillations are absent, is also analyzed. The electric-field strength of the ion-acoustic oscillations was determined from the broadening of the H_β line using formula (1). As a result of measurements, $\Delta\lambda_{1/2} = 1.8$ Å and $E_{\text{av}} \approx 18$ kV/cm, which for ion-acoustic oscillations gives a value of the degree of turbulence of $3 \cdot 10^{-2}$. The value of the ratio $w/N_{eT}e$, determined from the values of the anomalous resistance, is $1.2 \cdot 10^{-2}$ (the anomalous resistance of the plasma column is 1 ohm).

The electric-field strength of the ion-acoustic oscillations was also estimated from the wings of the H_α line. This line has 4π-components, whose intensity is $\sim 1/4$ of the intensity of the central component. The distance $\Delta\lambda$ between them is related to the mean field strength as follows:

$$\Delta\lambda = \frac{3}{\pi c}\frac{ea_0}{\hbar}\widetilde{E}_{\text{av}}.$$

In this case, by measuring the width of the H_α line at the level of 1/4 intensity, one can determine the value of E_{av}. In our experiments $\Delta\lambda_{1/4} \sim 2.9$ Å, which gives for E_{av} a value of ~ 27 kV/cm. This agrees sufficiently well with the value of the field strength obtained from the broadening of the H_β line.

The results obtained well reflect the ion-acoustic nature of the turbulent heating of plasma by current ([8]), and the values of the energy density of the ion-acoustic oscillations agree with those measured earlier ([9,10]).

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