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**Abstract**

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**PHYSICS**

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## A METHOD FOR MEASURING NONEQUILIBRIUM ELECTRIC FIELDS IN TURBULENT PLASMA FROM THE STARK BROADENING OF HYDROGEN SPECTRAL LINES

*(Presented by Academician E. K. Zavoisky, 20 III 1970)*

1. In a collisionless plasma, dissipation of the energy of the directed motion of charged particles occurs as a result of the development of a high level of turbulent electrostatic oscillations <sup>(1,2)</sup>. An important object in the study of plasma turbulence is collisionless magnetosonic shock waves propagating across the magnetic field <sup>(3,4)</sup>. The thickness of the front of such waves measured in our previous experiments,  $\delta_e \approx (6 \div 10)c/\omega_{pe}$  <sup>(5,6)</sup>, and the jump of the electron temperature at the front,  $\Delta T_e \approx 100 \div 300$  eV <sup>(5,7)</sup>, cannot be explained on the basis of binary-collision mechanisms. This would require an effective frequency  $\nu_{eff} \gtrsim 2 \cdot 10^9$  s<sup>-1</sup>, which exceeds the Coulomb value by two orders of magnitude <sup>(7)</sup>. Such a value of  $\nu_{eff}$  can be associated only with the development of turbulent electrostatic oscillations in the plasma. According to the theory <sup>(3,4)</sup>, several types of electrostatic plasma instabilities (beam, ion-acoustic, ion-ion) may occur in the transition zone of a shock wave, and the turbulence level of these oscillations

$$\xi = \int E_k^2 dk / 8\pi N T_e = \frac{\langle \tilde{E}^2 \rangle}{8\pi N T_e}$$

may exceed the equilibrium value  $\xi = (N r_D^3)^{-1}$  by several orders of magnitude. Here  $r_D = (v_{Te}/\omega_{pe})$  is the Debye radius.

Application of the theory of homogeneous turbulence of ion-acoustic waves to the conditions of the front of a collisionless magnetosonic shock wave shows that, in order to explain  $\nu_{eff} \gtrsim 2 \cdot 10^9$  s<sup>-1</sup>, a turbulence level  $\xi_i = W_i / N T_e = 10^{-3} \div 10^{-2}$  is required <sup>(8)</sup>. For characteristic plasma parameters  $N_e \sim 10^{14}$  cm<sup>-3</sup> and  $T_e \sim 50$  eV, the corresponding electric field strength of the oscillations may

exceed, by an order of magnitude, the mean interparticle field  $E_0 = 2.6 eN_e^{2/3}$ . To measure such fields it is natural to use the effect of Stark broadening of the spectral lines of hydrogen or hydrogen-like ions. The theoretical possibility of this was considered in <sup>(9,10)\*</sup>; experiments were reported in <sup>(11-13)\*\*</sup>.

According to <sup>(10)</sup>, the nature of the action of the nonequilibrium electric field of oscillations on an emitting hydrogen atom depends essentially on the frequency of variation of this field. High-frequency Langmuir oscillations ( $\omega \geq \omega_{pe}$ ) act nonadiabatically on the emitting atom, since their frequency is higher than the frequency of precession of the dipole moment of the atom

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\* In <sup>(9)</sup> the pattern of Stark broadening of hydrogen lines by high-frequency plasma oscillations in the adiabatic approximation was considered. In <sup>(10)</sup> a theory of line broadening in nonequilibrium electric fields was developed, taking nonadiabatic effects into account.

\*\* In <sup>(11)</sup> a spectroscopic investigation was carried out of a plasma produced by an external electron beam. In the experiments <sup>(12)</sup>, turbulent plasma in a toroidal system was studied. The profiles of hydrogen spectral lines were recorded from discharge to discharge with the aid of a monochromator and a photomultiplier. In the experiments <sup>(13)</sup>, by the same method, anomalous broadening of the lines of the hydrogen-like ion  $H_e^+$  in a collisionless shock wave was studied.

$$\omega_E = \frac{3}{2} \frac{na_0e}{\hbar} E.$$

Conversely, oscillations associated with the motion of ions (ion sound, ion-ion oscillations, etc.) act on the atom adiabatically ( $\omega_{ion} < \omega_E$ ), and in the most interesting range of parameters ( $N_e \gg 5 \cdot 10^{13} \text{ cm}^{-3}$ ,  $T_e \lesssim 50 \text{ eV}$ ) even quasistatically. At a high noise level at Langmuir frequencies, the half-widths of the Stark components of hydrogen lines may substantially exceed the values due to individual electron impacts. The maximum possible value of the line half-width  $\Delta\omega_{1/2} \approx \omega_{pe}$  is reached at the noise level  $\xi_e = W_e/NT_e \approx e^2/2n^4a_0T_e$ . In this case, for all lines for which the value of the principal quantum number of the upper level satisfies the inequality

$$n^4 \gg \frac{e^2}{2a_0T_e} \xi_e^{-1},$$

the half-widths  $\Delta\omega_{1/2}$  prove to be identical.

The broadening pattern changes substantially in the presence of intense low-frequency nonequilibrium electric fields acting quasistatically. In these fields there should be observed a splitting of lines that do not possess a central Stark

component  $(L_{\gamma-\beta}, H_{\beta}, H_{\delta})$ . The splitting is especially pronounced at a turbulence level  $\xi_i \gg e^2 N^{1/3} / T_e$  and in the absence of turbulence at Langmuir frequencies. Nonequilibrium Langmuir oscillations will not affect the lifetime of the atom on the Stark sublevels in those cases where the turbulence level of the low-frequency oscillations exceeds the value  $\xi_i^{cr} \approx e^2 / 2n^2 a_0 T_e$ . This means that, with a gradual increase of the level  $\xi_i$  in a turbulent plasma with strong nonequilibrium fields also at Langmuir frequencies ( $\xi_e \gg e^2 / 2n^4 a_0 T_e$ ), the line profiles will rather sharply change their shape from “smeared,” with half-width  $\Delta\omega_{1/2} \approx \omega_{pe}$ , to split into separate groups of components.

2. The experiments were carried out on the UV-2 installation <sup>(6)</sup>. By the method of high-speed electro-optical spectrochronography <sup>(14)</sup>, nonequilibrium electric fields in a collisionless shock wave were measured from the Stark broadening of hydrogen lines.\* An IT-51 interferometer crossed with an ISP-51 spectrograph was used. Observations were made from the end of the discharge chamber in a direction parallel to the magnetic field. The shock circuit, operating in the  $\theta$ -pinch mode, was switched on with a delay  $t_z$  relative to the preliminary-ionization discharge. The synchronization and the spectrum-sweep rate were chosen so that, on the same spectrochronogram, it was possible to determine the plasma density  $N_1$  ahead of the wave front and to measure the line half-width at the front and behind the wave front.

The experiments were carried out at an initial pressure  $P_0 = 5 \cdot 10^{-3} - 10^{-2}$  mm Hg, a constant magnetic field  $H_1 = 500 \div 750$  Oe, and two values of the delay  $t_z = 140$  and  $40 \mu s$ . In the first case  $N_1 \approx 8 \cdot 10^{13} \text{ cm}^{-3}$  and the degree of ionization  $N_e / (N_e + N_a) \approx 0.2$ . The magnetic field  $\hat{H}$  under the shock winding during the propagation of the wave in the plasma had time to rise to the value  $\hat{H}_n \approx 400$  Oe. In the second case  $N_1 = (3 \div 4) \cdot 10^{14} \text{ cm}^{-3}$ ,  $N_e / (N_e + N_a) \approx 1$ , and  $\hat{H}_n = 700 - 800$  Oe.

Spectrochronogram 1 in Fig. 1 was recorded in the light of the  $H_{\beta}$  line for the preliminary-ionization plasma produced by the current of a direct discharge. The line profile ahead of the shock-wave front is given in Fig. 2a (curve 1). Its half-width is  $\Delta\lambda_{1/2} \approx 1.2 \text{ \AA}$ . Spectrochronogram 2 was obtained during operation of the shock circuit with  $t_z = 40 \mu s$ . The bright glow in the initial phase corresponds to the shock-wave front. The line profile in this phase in Fig. 2a is shown by curve 2. Its half-width is of the order of, or greater than, the dispersion region  $\Delta\lambda_s = 4 \text{ \AA}$ , and is 3.5 times greater than the half-width ahead of the wave front. If one takes into account the increase of density at the wave front due to

\* The first experimental results obtained in this way were published in <sup>(15)</sup>. Similar measurements of the turbulence level in a plasma with current flowing along the magnetic field were carried out in <sup>(16)</sup>.

**Fig. 1.** Spectrochronograms of the  $H_{\alpha}$  and  $H_{\beta}$  lines obtained with a Fabry-Perot interferometer crossed with an ISP-51 spectrograph: 1 —spectrochronogram

Figure 1. Spectrochronograms of the  $H_\alpha$  and  $H_\beta$  lines obtained with a Fabry-Perot interferometer crossed with an ISP-51 spectrograph: 1 – spectrochronogram of the  $H_\beta$  line in a preionization plasma; 2 – spectrochronogram of the  $H_\beta$  line when the shock circuit is switched on with a delay  $t_3 = 40 \mu\text{s}$ ; 3 – the same with a delay  $t_3 = 140 \mu\text{s}$ ; 4 – spectrochronogram of the  $H_\alpha$  line when the shock circuit is switched on with a delay  $t_3 = 140 \mu\text{s}$  (contains one order of interference)

Figure 1: Figure 1. Spectrochronograms of the  $H_\alpha$  and  $H_\beta$  lines obtained with a Fabry-Perot interferometer crossed with an ISP-51 spectrograph: 1 – spectrochronogram of the  $H_\beta$  line in a preionization plasma; 2 – spectrochronogram of the  $H_\beta$  line when the shock circuit is switched on with a delay  $t_3 = 40 \mu\text{s}$ ; 3 – the same with a delay  $t_3 = 140 \mu\text{s}$ ; 4 – spectrochronogram of the  $H_\alpha$  line when the shock circuit is switched on with a delay  $t_3 = 140 \mu\text{s}$  (contains one order of interference)

Fig. 2

Figure 2: Fig. 2

gram of the  $H_\beta$  line in a preionization plasma; 2 – spectrochronogram of the  $H_\beta$  line when the shock circuit is switched on with a delay  $t_3 = 40 \mu\text{s}$ ; 3 – the same with a delay  $t_3 = 140 \mu\text{s}$ ; 4 – spectrochronogram of the  $H_\alpha$  line when the shock circuit is switched on with a delay  $t_3 = 140 \mu\text{s}$  (contains one order of interference)

freezing, then the normal Stark broadening should have been  $\Delta\lambda_{1/2} \approx 1.8 \div 2 \text{ \AA}$ . Therefore, the observed broadening of the  $H_\beta$  line cannot be explained by the action of the equilibrium interparticle microfield. If this broadening is attributed to the quasistatic action of nonequilibrium electric fields, then for the corresponding field strength we obtain  $\langle \tilde{E} \rangle_{ion} \geq 7 \text{ kV/cm}$ . Estimating the density of thermal energy from the magnitude of the alternating magnetic field absorbed by the plasma,  $NT_e \approx 0.3\hat{H}_n^2/8\pi$ , we obtain for the turbulence level

$$\xi_i = \langle \tilde{E}^2 \rangle / 8\pi NT_e \gtrsim \langle \tilde{E} \rangle^2 / 8\pi NT_e = \langle \tilde{E} \rangle^2 / 0.3\hat{H}_n^2 \gtrsim 3 \cdot 10^{-3}.$$

**Fig. 2.** Profiles of the  $H_\beta$  line, obtained by photometry of spectrochronograms 1, 2, and 3 of Fig. 1: *a*–at  $t_3 = 40 \mu\text{sec}$ , *b*–at  $t_3 = 140 \mu\text{sec}$ . 1–before the front, 2–at the shock-wave front; profile 3 was obtained with the aid of a standard hydrogen lamp to determine the instrumental half-width.

This value is in qualitative agreement with theoretical estimates based on the model of homogeneous turbulence of ion-acoustic oscillations <sup>(8)</sup>.

At  $t_3 = 40 \mu\text{sec}$ , the half-width of the line behind the wave front also proves to be greater than  $\Delta\lambda_s = 4 \text{ \AA}$ . A broadening effect not exceeding  $\Delta\lambda_s$  is obtained at the larger delay  $t_3 = 140 \mu\text{sec}$ , when the plasma density  $\hat{N}_1 \approx 8 \cdot 10^{13} \text{ cm}^{-3}$

Figure 3: Line profiles

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and the magnetic field  $\hat{H}_n$  under the shock coil increases only to 400 Oe. Accordingly, the level of nonequilibrium quasistatic oscillations, determined by analogy with the preceding case from the microphotograms of Fig. 2b, here proved lower:  $\langle \tilde{E} \rangle_{ion} \approx 3$  kV/cm. An important detail of spectrochronogram 3 is an additional intensity maximum in the interval between the two main (undisplaced) interference maxima. It appears as a result of splitting of the  $H_\beta$  line in nonequilibrium quasistatic fields behind the shock-wave front, and the magnitude of the splitting corresponds to a field strength  $\langle \tilde{E} \rangle_{ion} \approx 15$  kV/cm. The turbulence level here reaches the value  $\xi_i \approx 5 \cdot 10^{-3}$ , which exceeds the critical value determined in <sup>(10)</sup>,  $\xi_i^{cr} = e^2/2n^2a_0T_e$ , for  $n = 4$ ; therefore such splitting can occur even in the presence of a high level of Langmuir-oscillation turbulence. The transition from a smooth profile at the shock-wave front to splitting behind the front may be interpreted as the result of the growth of low-frequency turbulence in the process of the subsequent compression of the plasma by the magnetic piston. At the front itself,  $\xi_i$  remains below critical, and the “smooth” character of the profile and its half-width  $\Delta\omega_{1/2} \approx \omega_{pe}$  indicate the presence also

of a high level of turbulence of the Langmuir oscillations  
 $\xi_e \gg e^2/2n^4a_0T_e \approx 10^{-3}$ .

Spectrochronogram 4 in Fig. 1 was obtained in the light of the  $H_\alpha$  line under conditions identical to those for spectrochronogram 3, but with a somewhat higher sweep rate (dispersion region  $\Delta\lambda_s = 7.2 \text{ \AA}$ ). Two important details attract attention: a strong broadening of the line profile at the front and its subsequent sharp narrowing behind the wave front (the photometry results are shown in Fig. 3).

**Fig. 3.** Profiles of the  $H_\alpha$  line obtained by photometry of spectrochronogram 4 of Fig. 1. 1—before the front, 2—at the front, and 3—behind the front of the shock wave.

The half-width of the  $H_\alpha$  line ( $n = 3$ ) and of the  $H_\beta$  line ( $n = 4$ ) at the wave front coincides with good accuracy with the Langmuir frequency  $(\Delta\omega)_{1/2} \approx \omega_{pe}$ . From this one can obtain a more precise estimate of the level of high-frequency turbulence,

$$\xi_e \gg e^2/2n^4a_0T_e \simeq e^2/162a_0T_e \approx 5 \cdot 10^{-3}.$$

The sharp decrease in the half-width of  $H_\alpha$  behind the wave front apparently indicates rapid relaxation of the Langmuir oscillations and growth of the level of low-frequency turbulence.

Thus, the experiments described here show that the effect of Stark broadening of

the spectral lines of hydrogen, when the method of high-speed electron-optical spectrochronography is used, makes it possible to establish the presence and nature of nonequilibrium electric fields in a plasma, to measure the level of turbulence, and to trace the dynamics of the development of a nonequilibrium state in different phases of a fast process. These possibilities of the method are also confirmed by the results of experiments <sup>(16)</sup>.

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