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THE PHYSICAL BASES OF SPECTROSCOPIC MEASUREMENTS OF ELECTRICAL FIELDS IN A PLASMA

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Consideration is given to the chief spectroscopic methods of measuring electric fields in plasma media. These methods are based on the effects of Stark splitting of spectral lines of hydrogen atoms, and the appearance of forbidden (by parity) components in the emission spectra of helium atoms. An analysis is made of methods of measuring weak electric fields (with intensities from 10 to 100 V/cm) in plasma. The methods are based on the appearance of forbidden components in the spectra of laser-induced fluorescence of diatomic polar molecules and the Stark effect of Rydberg atoms.

The intraplasma electric field (EF) is one of the most important parameters determining the state and physical processes in a plasma. The EF in a plasma may be caused by natural oscillations of the plasma (e.g., of the Langmuir or ion-acoustic types), the penetration into the plasma from external sources of radiation (e.g., laser or microwave), or the presence of a volume charge (e.g., in the cathode layer of a glow discharge). Furthermore, at every point of a plasma there is an EF created by separate ions and electrons. We note also that the EF may be of the Lorentz type $F_L = c^{-1}[\mathbf{v} \times \mathbf{B}]$ in the case when in the plasma, situated in a magnetic field of strength **B**, an atomic beam is injected with velocity **v** (for the purpose of heating or diagnostics of the plasma). At the present time, for EF measurements in a plasma, wide use is made of spectroscopic methods based on the Stark effect of atoms, ions and molecules in the plasma. These methods are generally divided into the following groups.

1. Methods of Measuring the EF from the Spectra of Hydrogen Atoms. Since atoms of hydrogen (or deuterium) possess, in their excited states, constant dipole moments, their spectra are very sensitive to the effect of the EF. At the present time, after thorough investigation, wide use is being made in plasma diagnostics of the Stark splitting effect and broadening of spectral lines (SL) of hydrogen atoms in quasistatic (QS) intraplasma EF **F**. In recent work [1], from the magnitude of the Stark splitting of hydrogen SL, taking into the fine structure of atomic levels, the EF has been measured in the cathode layer of a glow discharge in hydrogen. In [2], from the QS broadening of H_α and H_β SL, a low-frequency anisotropic turbulence has been found in the cathode region of a glow discharge at atmospheric pressure in helium. For measuring the quasimonochromatic linearly polarized EF of the form $E_{lin}(t) = E_0\cos(\omega t + \varphi)$, use is made of the appearance of satellites in the emission spectrum of atomic hydrogen, which stand apart from the undisplaced position of the hydrogen SL by frequencies $\Delta\omega = \pm p\omega$ (p = 1, 2, 3...). The reason for the appearance of the satellites at frequencies $\Delta\omega = \pm p\omega$ (see [3]) is that in a field $E_{lin}(t)$, the hydrogen atom wave function in the α state is described by the expression $\exp[-i(\mathbf{d}_{\alpha\alpha}\cdot\mathbf{E}_0/\omega)\sin(\omega t + \varphi)$, where $\mathbf{d}_{\alpha\alpha}$ is the dipole moment of the atom in the α state. The appearance of satellites of the hydrogen SL from the effect of a field $E_{lin}(t)$ was first used in [4] for measuring UHF

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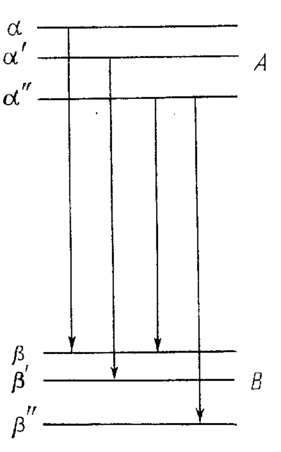

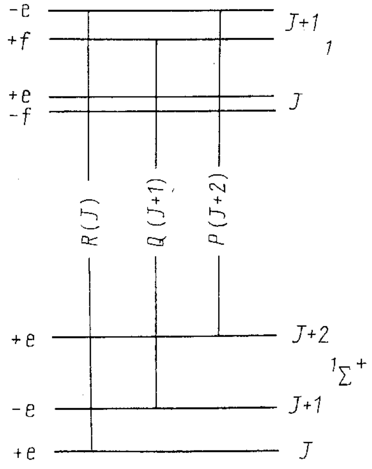

Fig. 1

Fig. 2

Fig. 1. Diagram of the energy levels of a nonhydrogenlike atom. The arrows denote permitted electric dipole transitions.

Fig. 2. Diagram of the energy levels of a diatomic polar molecule for transitions $^1\Pi$ $^1\Sigma^+$. Permitted electric dipole transitions are shown by the vertical lines.

fields in a pulsed UHF discharge (f ≈ 9.4 GHz) from the profile of the H_β SL. It should be noted, however, that in [4], individual satellites were not observed, but the profile of the envelope of the satellites was recorded. In [5], the appearance of satellites $\Delta\omega = \pm\omega$ of the D_β, D_γ, and D_δ SL of deuterium enabled measurements to be made in a plasma of EF $E_{\text{lin}}(t)$ from UHF radiation at frequency 34.8 GHz. In [6, 7], a method is proposed for laser-fluorescent measurements of UHF EF in a plasma. The basis of this method is the dependence of the fluorescence signal on the intensity of the UHF wave with the laser frequency tuned to resonate with the transition frequency of any of the hydrogen SL. This method enabled measurements to be made [7] of the intensity of the UHF EF at frequency f = 38.5 GHz, from the fluorescence signal in the H_α transition. For recording the satellites of hydrogen and deuterium in a field $E_{\text{lin}}(t)$, the technique of intraresonator laser spectroscopy was used in [8]. In [9], a theory was developed, based on calculation of the SL splitting of hydrogenlike atoms, for measuring the parameters of an elliptically polarized UHF field in a plasma (such waves are used, in particular, for supplementary heating of the plasma in installations of the Tokamak type). The methods considered above for measuring the parameters of oscillating EF E(t) in a plasma, from the SL of hydrogenlike atoms, are applicable in the case when $|E(t)| >> \langle F\rangle$, where $\langle F\rangle$ is the characteristic intensity of the QS intraplasma EF **F**. The EF **F** may represent the microfield of ions, or the EF of low-frequency plasma turbulence. If the inequality $|E(t)| >> \langle F\rangle$ is invalidated, then for measuring the EF E(t), it is possible to use the effects of modification of the QS profile of the hydrogen SL (taking account of the distribution function of the fields **F** in the plasma), attributable to the influence of the EF **E**(t). Relevant to this is, firstly, the appearance of characteristic "reliefs" in definite places of the QS Stark profiles of hydrogen SL (for full account, see [10-12]). These "reliefs" correspond to the origin of resonance between the frequency of the field E(t) and the Stark splitting of the upper or lower energy level of the hydrogen atom in the EF **F**. In [10], by recording the "reliefs" in the profiles of SL D_α, D_β, and D_γ high-frequency plasma turbulence in the Z-pinch was discovered and investigated. Secondly, relevant here is the appearance of satellites $\Delta\omega = \pm\omega$ in the QS profiles of hydrogen SL. These satellites have a different physical nature, and different quantitative characteristics from the Blochinzew satellites considered above, and arise only from the joint action on a hydrogen atom of fields **F** and **E**(t) (for full account, see [11]). Finally, in the situation when $\omega >> n\hbar\langle F\rangle/(m_e e)$, $[n\hbar|E(t)|\omega/(m_e e)]^{1/2} >> n\hbar\langle F\rangle/(m_e e)$, where n is the principal quantum number of the upper energy level of the hydrogen atom, the field **E**(t) suppresses the component of the QS field **F** orthogonal to it and thus reduces the half-width of the QS hydrogen profiles. In [13], based on this effect in the peripheral zone of the plasma column of a T-10 Tokamak, intense oscillatory EF were discovered, and their parameters analyzed.

2. Methods of Measuring EF from the Spectra of Nonhydrogenlike Radiations. In many situations, in the energy spectrum of nonhydrogenlike radiations (from atoms or ions), two relatively isolated subsystems of energy levels may be picked out: the upper A = {α, α′, α″, ...} and lower B = {β, β′, β″, ...} (see Fig. 1), where, in the absence of external EF, permitted (by parity), are only some of the transitions between levels belonging to the subsystems A and B (in Fig. 1, such permitted transitions are shown by arrows). The external EF may shift the levels of the upper, A, and/or the lower, B, subsystems. This leads to the appearance in the emission spectrum in the transition A → B, side by side with permitted (P) SL, also forbidden (F) SL (for the case when the EF is static), or satellites of FSL [14]), standing apart from the positions of the FSL by frequency $\Delta\omega = \pm\omega$ (for the case when the EF is quasimonochromatic at frequency ω). Furthermore, under the influence of the EF, there occurs a Stark shift of the positions of the levels belonging to the subsystems A and B, and corresponding SL in the transition A → B. Therefore, the intensity of the electric field in the plasma may be measured, either in relation to the intensities of the FSL and PSL, or from the shift of the positions of the FSL and/or PSL. The direction of the EF in a plasma can be determined by registering the polarization of the radiation in FSL (or corresponding satellites). To determine the intensity of QS EF **F** in a discharge with hollow cathode in helium [15], the ratio of the intensities of two SL of HeI was used: PSL 396.5 nm ($4^1P \to 2^1S$) and FSL 491.1 nm ($4^1P \to 2^1P$). The direction of the EF was determined from the polarization of FSL 491.1 nm. From the Stark frequency shift of the permitted transition 7d[5/2]3 − 4p[3/2]2, in argon, the intensity of the EF was measured, and the charge distribution found in the cathode layer of the discharge with a hollow cathode in argon [16]. In [17], from the ratio of the intensities of two SL of HeI (FSL 663.2 Å ($3^1P \to 2^1P$), and PSL 501.6 nm ($3^1P \to 2^1S$)) a measurement was made of the intensity of the turbulent EF, arising with the passage of a relativistic electron beam through a helium plasma. For measuring the intensity of the EF of high-frequency plasma turbulence arising with the passage of nonrelativistic electron beam through a helium plasma, use was made in [18] of the ratio of the intensities of satellites $\pm\omega$FSL HeI 447.0 nm ($4^3F \to 2^3P$) and the intensities of PSL HeI 447.1 nm ($4^3D \to 2^3P$). In [19], by recording the satellites $\pm\omega$ of two FSL of HeI 492.1 nm ($4^1F \to 2^1P$) and HeI 447.0 nm ($4^3F \to 2^3P$), the intensity was measured, and the direction determined, of the oscillatory EF in the region of the plasma resonance from interaction of powerful UHF wave with nonhomogeneous plasma. In essence, local measurements of the EF were made by comparing the experimental ratios of the intensities of the near and distant satellites of FSL with the corresponding theoretical functions. In [20], from the Stark broadening of the SL of lithiumlike ions CIV, NV and OVI, the EF was measured in the plasma turbulence in a "current layer" installation.

3. Methods of Measuring Weak EF. Methods for diagnosing an EF in a plasma, considered in Secs. 1 and 2 enable EF measurements to be made for intensities $E \geq 300$ V/cm. For measuring weaker EF, including those with $E \sim 10$ V/cm, two high-sensitivity methods have been developed in recent years. One of these is based on the appearance of FSL in the spectrum of laser-induced fluorescence of diatomic polar molecules, and the other, on the Stark splitting of high-excitation (Rydberg) atomic levels.

1) The method of measuring static EF **F** from the spectra of laser-induced fluorescence (LIF) of diatomic polar molecules was proposed in [21]. The crux of the method consists of the following. Let the basic electron state of the molecule be $^1\Sigma^+$, and the upper state $^1\Pi$ (Fig. 2). Each rotary level J of state $^1\Pi$ is split into two close sublevels, Λ-double e and f, connected with dipole transition. If the laser radiation is tuned in resonance with the transition $(^1\Sigma^+, J) - (^1\Pi, J + 1)$, belonging to the R branch, then in the absence of an external EF **F**, there will be present in the LIF spectrum PSL belonging to R- and P-branches. For $F \neq 0$, there occurs a displacement of the states of sublevels e and f. As a result, in the LIF spectrum, together with the PSL referred to above, there appears also a FSL, belonging to the Q-branch. The intensity of the EF **F** may be measured from the ratio of the intensities of components belonging to Q- and P-branches. Since the splitting Λ-doubling Δ_{ef} may be very small ($\Delta_{ef} \sim 10^{-4} - 10^{-5}$ cm^{-1}), the method described above permits measurements to be made of weak EF with $F_{min} \sim (5-10)$ V/cm. For measuring the EF in the plasma of a radiofrequency discharge, LIF with the molecule BC1 was used [21]. In [22], LIF with NaK molecules was used for measuring the distribution of the electric fields in the plasma of two types of discharge: a) radiofrequency discharge; b) constant current discharge in the transitional regime with the additional action of radiation from a pulsed laser, for the purpose of increasing the rate of photoelectron emission from the material of the cathode. In [23], based on calculation of the modification in the LIF spectra of diatomic polar molecules under the influence of UHF EF, a method is proposed for measuring weak UHF EF in a plasma.

2) A method of measuring the EF based on Stark spectroscopy of Rydberg atoms of helium was first realized in [24, 25] for diagnostics of the spatial distribution of the EF in the cathode layer and positive column of a glow discharge. The method is based on recording Stark splitting of high-excitation levels of atoms under the influence of the EF. The high sensitivity of Rydberg atoms to the action of EF is caused by the fact that in the high-excitation states, the atoms have large dipole moments, and, consequently, under the influence of the EF, the high-excitation levels suffer significant Stark splitting. In the method considered, high-excitation Stark sublevels are populated by excitation by means of radiation of a tuned laser, from one of the low-lying states (in the case of HeI, such low-lying states may be 2^1S, 2^3S, 2^1P, 2^3P), and recorded by means of the optogalvanic effect. In [26], it was demonstrated experimentally that by means of Stark spectroscopy of Rydberg atoms, not only the intensity

of the EF F, but also its gradient dF/dz may be measured simultaneously. In this case, the possibility of measuring the gradient dF/dz derives from the nonuniform broadening of individual Stark components of Rydberg atoms, excited by radiation from a laser, taking into consideration the finite diameter of the laser beam.

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