Observation and analysis of oscillating electric fields in the peripheral plasma in a tokamak on the basis of a new spectroscopic effect

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Intense oscillating electric fields have been discovered by a spectroscopic method in the peripheral zone of the plasma column in the T-10 tokamak. The parameters of these fields are analyzed.

1. The peripheral plasma has recently been attracting considerable interest in fusion research in tokamaks because very slight changes in the parameters of this plasma can lead to a fundamental change in the structure of the overall plasma column and changes in the particle lifetime.[1] In the present letter we report a study of the peripheral plasma in the T-10 tokamak through an analysis of deuterium lines. The deuterium-line emission spectrum was measured along a central chord in the equatorial plane of the device. The diagnostic apparatus, consisting of a ten-channel polychromator using an MDR-2 monochromator with fiber optics and photomultipliers, makes it possible to measure the spectrum in a single discharge. The resolution of the individual channels is 0.6–0.7 Å. A polarizer is placed in front of the entrance slit of the polychromator for a polarization analysis of the emission.

Figures 1 and 2 are typical spectra of the deuterium lines D_α, D_β, and D_γ, in this case measured at a device magnetic field $B_0 = 1.65$ T. The most prominent feature on

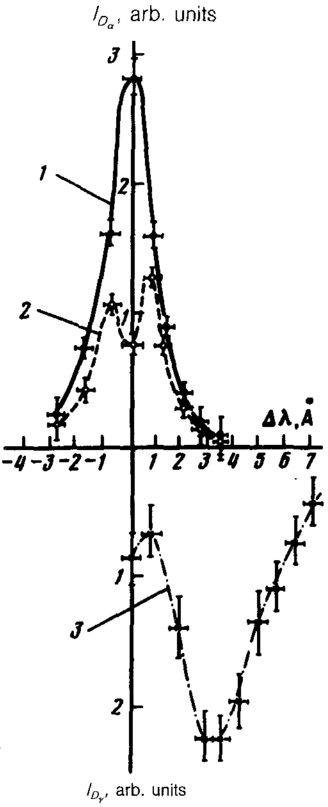

FIG. 1. Profiles of the D_α line (curves 1 and 2) and the "red" half of the profile of the D_γ line (curve 3), measured at a discharge current $J = 180$ kA, at a device magnetic field $B_0 = 1.65$ T, and at an electron density $\bar{n}_e \approx 2.5 \cdot 10^{13}$ cm^{-3}. 1—The polarization of the emission is $\mathbf{e} \perp \mathbf{B}_0$; 2, 3—$\mathbf{e} \| \mathbf{B}$.

these profiles is a dip in the central part of the D_α and D_γ profiles, but not on the D_β profile. The dips in the D_α and D_γ lines are observed on the profiles corresponding to emission with polarization parallel to the vector $\mathbf{B}_0$ (π profiles). The dips on the deuterium polarization profiles cannot be explained either by a Zeeman splitting

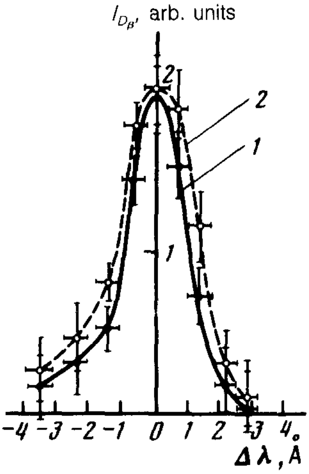

FIG. 2. The same as in Fig. 1, but for the D_β line. 1—$\mathbf{e} \perp \mathbf{B}_0$; 2—$\mathbf{e} \| \mathbf{B}_0$.

(since it would be smaller than the observed splitting by a factor of 2–2.5 and, furthermore, could not arise on π profiles) or by a self-absorption of the emission (since there are no dips on the D_α and D_γ profiles in the other polarization or on any of the D_β profiles). The only physical mechanism which might be responsible for the appearance of these dips is a Stark effect in anisotropic electric fields. Here there is the question of the particular form of these fields. The presence of dips on the π profiles of D_α and D_γ at $B_0 = 1.65$ T could in principle be explained on the basis that quasimonochromatic electric fields with an amplitude $E_0 \gg m_e e\omega/n^2\hbar$ (ω is the frequency of the fields and n is the principal quantum number) are excited along the magnetic field of the device, $\mathbf{B}_0$ (Refs. 2 and 3). This interpretation, however, would require that a dip also be present on the π profile of D_β, at odds with the observations.

2. It turns out that the spectral features on the set of polarization profiles of D_α, D_β, and D_γ at $B_0 = 1.65$ T can be explained on the basis of a superposition of an rf quasimonochromatic electric field $\mathbf{E}_0 \cos \omega t$, polarized along the observation direction, and a quasistatic electric field[1] $\mathbf{F} \| \mathbf{B}_0$:

$$\mathbf{E}(t) = \mathbf{e}_z E_0 \cos \omega t + \mathbf{e}_x F \tag{1}$$

($\mathbf{e}_x$ and $\mathbf{e}_z$ are unit vectors). In a situation with $\max[\omega, (n\hbar E_0\omega/m_e e)^{1/2}] \gg n\hbar F/m_e e$, the imposition of field (1) on hydrogen-like radiator gives rise to a fundamentally new spectroscopic effect: The quasimonochromatic electric field $\mathbf{e}_z E_0 \cos\omega t$ *suppresses* the quasistatic component $\mathbf{e}_x F$ which is orthogonal to it. As a result, the effective quasistatic field acting on the level n of the deuterium atom is $\mathbf{e}_x F_{\text{eff}}^{(n)}$, where $F_{\text{eff}}^{(n)} = F \cdot J_0(3n\hbar E_0/2m_e e\omega)$ [$J_0(u)$ is the Bessel function]. Furthermore, in the spectrum with the z polarization, under the condition $3n\hbar E_0/2m_e e\omega \gtrsim 1$, satellites may exist at distances $\Delta\omega = \pm\omega, \pm 2\omega, \ldots$, from the center of the line; these satellites are comparable in intensity to the component at the frequency $\Delta\omega = 0$.

The presence of dips on the π profiles of D_α and D_γ and the absence of a dip from the π profile of D_β can thus be explained on the basis that the quasimonochromatic electric field $\mathbf{E}_0 \cos\omega t$ partially suppresses the quasistatic splitting of the $n = 2$, 3, 5 levels and *completely* suppresses that of the $n = 4$ level $F_{\text{eff}}^{(4)} = 0$. Since in the case $F_{\text{eff}}^{(4)} = 0$ the most intense π and σ spectral components of the quasistatic profile of D_β are emitted at an unshifted frequency, $\Delta\omega = 0$, there is no dip at the center of the π profile of D_β. Under the assumption that for $n = 4$ the argument of the function $J_0(3n\hbar E_0/2m_e e\omega)$ is the same as the first zero of this function, we find $\hbar E_0/m_e e\omega \approx 0.40$. Hence, under the condition that the frequency ω is near the electron cyclotron frequency ω_{ce} at ($B_0 = 1.65$ T), we find $E_0 \approx 14$ kV/cm. In this case the values of $F_{\text{eff}}^{(n)}$ for the other levels are $F_{\text{eff}}^{(2)} \approx 0.67F$, $F_{\text{eff}}^{(3)} \approx 0.34F$, $F_{\text{eff}}^{(5)} \approx 0.26F$. An estimate of the quasistatic fields from the π profile of D_α yields $F \approx 20$ kV/cm. It follows from Figs. 1 and 2 that the intensities of the σ and π profiles integrated over the spectrum differ by a factor of about two for the D_α line and are nearly the same for the D_β line. The probable explanation is that the populations of the Stark sublevels of the $n = 3$ level, which are split by the field $F_{\text{eff}}^{(3)}$, are not the same as their equilibrium values, while the Stark sublevels of the $n = 4$ level with $F_{\text{eff}}^{(4)} = 0$ remain equal in energy, and collisions cause their populations to become equal. The direction of the quasimonochromatic electric field $\mathbf{E}_0 \cos\omega t$ is approximately along the observation direction, since the σ profiles of

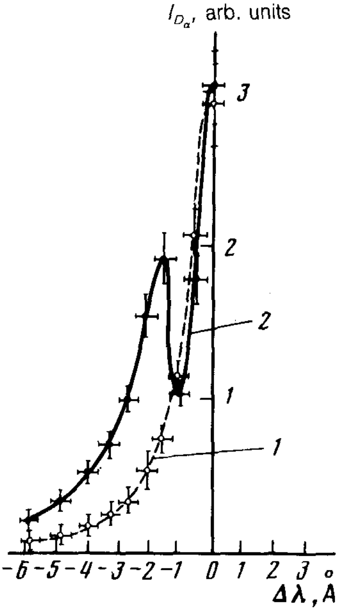

FIG. 3. Profiles of the D_α line (the "blue" half) measured at $J = 450$ kA, $B_0 = 3.05$ T, and $\bar{n}_e \approx 6 \cdot 10^{13}$ cm^{-3}. 1—$\mathbf{e} \| \mathbf{B}_0$; 2—profile measured without a polarizer.

D_α and D_β have no intense satellites at the frequencies $\Delta\omega = \pm\omega, \pm 2\omega, \ldots$. A determination of the ion temperature from the measured halfwidth of the spectral component of the σ profile of D_α yields $T_i \sim 10$–15 eV, in agreement with the estimates $T_i \sim 10$–30 eV found for the region of the maximum intensity of the deuterium lines by other methods, for various operating conditions in the T-10.

3. At a stronger magnetic field, $B_0 = 3.05$ T, the profiles of the deuterium lines change substantially: It is the σ profile of D_α, not the π profile, which has the greater broadening and the central dip (Fig. 3). These results mean that the quasistatic field is now directed along the y axis (perpendicular to $\mathbf{B}_0$ and to the observation direction). A quantitative analysis of the σ profile of D_α in Fig. 3 yields $F \sim 20$ kV/cm (and, as before, $\Omega \ll \omega_{ce}$), $0 \lesssim 10$ kV/cm.

4. In summary, an analysis of the experimental data on the basis of this new spectroscopic effect shows that oscillations grow to electric fields of 10–20 kV/cm at least in the peripheral plasma of the T-10 tokamak under conditions with a high current and a comparatively low density. We note in conclusion that the quasistatic component does not necessarily represent a regular, one-dimensional, low-frequency quasimonochromatic electric field. The results of our analysis of the experimental profiles of D_α, D_β, and D_γ are also consistent with the conclusion that the quasistatic component represents a low-frequency turbulence with a quasi-two-dimensional spectrum, which has developed in the xy plane (at $B_0 = 1.65$ T) or the yx plane (at $B_0 = 3.05$ T).

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[1] The field F is a low-frequency quasimonochromatic electric field $\mathbf{F}\cos\Omega t$. The quasistatic nature of the effect of this field is a consequence of the condition[3] $\Omega \ll n^2\hbar F/m_e e \ll (\delta\Omega)^3/\Omega^2$ where $\delta\Omega$ is the scale value of the total broadening caused by other mechanisms.

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[1] A. A. Bagdasarov, V. I. Bugarya, N. L. Vasin, and V. A. Vershkov, Proceedings of the Twelfth European Conference on Controlled Fusion and Plasma Physics, Budapest, 1985, p. 207.

[2] D. I. Blochinzew, Phys. Z. Sow. Union **4**, 501 (1933).

[3] E. A. Oks and Yu. M. Shagiev, Preprint No. 76, Institute of Applied Physics, Academy of Sciences of the USSR, Gor'kiĭ, 1983.

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