Computation of radial electric field in the turbulent edge plasma of the T -10 tokamak

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It is widely recognized that the radial electric field E_r plays an important role in plasma confinement via [E_r x B_{tor}] shearing stabilization mechanism. Theoretical description of the formation of E_r based on turbulent dynamics and, specifically, numerical modeling of the edge plasma electrostatic pote ntial in the T-10 tokamak is the goal of this paper.

It has been shown experimentally by the direct measurements of Heavy Ion Beam Probe Diagnostics (HIBP), that electrostatic potential forms negative well ($E_r = -\frac{d\Phi}{dr} < 0$) for Ohmic and ECRH regimes with moderate densities (n_e = 1.5 - 2.5x10^{13} cm^{-3}) in the T-10 tokamak [1, 2]. Transition from OH to ECRH regime was accompanied by the decrease of the absolute potential value, i.e. module of radial electric field decreased , $|E_r|^{ECRH} < |E_r|^{OH}$, while its sign still remains negative.

Numerical simulation of the T-10 regimes was based on solution of nonlinear MHD equations in the frame of reduced two-fluid Braginskii's hydrodynamics [3]. Approach of the plane geometry (x,y,z) for magnetic field $\mathbf{B} = B_{0z}(x)\mathbf{e}_z + B_{0y}(x)\mathbf{e}_y$, $B_{0z} = B_0(1-\frac{x}{R})$, $B_{0y} = \frac{B_0 \varepsilon}{q(r)}$, where R and a – major and minor radii of the torus, q is the safety factor, $\varepsilon = \frac{a}{R}$ was used. The dimensionless system of MHD equations in the electrostatic approach has the form [3]:

$$\frac{DW}{Dt} + H_{NL} = -\nabla_{\parallel} J - g_B \frac{\partial p}{\partial y} + \nu_{\perp} \cdot \Delta_{\perp} W, \qquad (1)$$

$$\frac{Dn}{Dt} = -\nabla_{\parallel} J + g_B \frac{\partial (N_0 \phi - p_e)}{\partial y} + D_{\perp} \cdot \Delta_{\perp} n, \qquad (2)$$

$$\frac{3}{2}\frac{Dp_e}{Dt} = -\frac{5}{2} T_{e0} \nabla_{\parallel} J + \frac{5}{2} g_B K_e - w_{ei} + \chi_{\parallel e} \nabla_{\parallel}^2 p_e + \chi_{\perp e} \cdot \nabla_{\perp}^2 p_e, \qquad (3)$$

$$\frac{3}{2}\frac{Dp_i}{Dt} = -\frac{5}{2} T_{i0} \nabla_{\parallel} J + \frac{5}{2} g_B K_i + w_{ei} + \chi_{\parallel i} \nabla_{\parallel}^2 p_i + \chi_{\perp i} \cdot \nabla_{\perp}^2 p_i, \qquad (4)$$

$$\eta_0 J = -\nabla_{\parallel}(\phi - p_e / N_0), \qquad (5)$$

$$K_e = p_{e0}\frac{\partial\phi}{\partial y} - 2T_{e0}\frac{\partial p_e}{\partial y} + T_{e0}{}^2\frac{\partial n}{\partial y}, \qquad K_i = p_{i0}\frac{\partial\phi}{\partial y} + T_{i0}\frac{\partial(p_i - p_e)}{\partial y} - T_{i0}{}^2\frac{\partial n}{\partial y},$$

$$W = \rho^2\cdot\nabla_\perp(n\nabla_\perp\phi + \nabla_\perp p_i), \qquad p = p_e + p_i. \qquad (6)$$

Here

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \{\phi,\ \}, \qquad \{A,B\} = \mathbf{e}_z\nabla A\times\nabla B,$$

$$g_B = \frac{2d}{R_0}, \quad \eta_0 = \frac{\nu_{ei}}{\omega_{ce}}, \quad \chi_{\|e} = \frac{3.16\omega_{ce}}{\nu_{ei}}, \quad \chi_{\|i} = \frac{3.9\omega_{ci}}{\nu_{ii}}, \quad w_{ei} = 3\frac{m_e}{M_i}\frac{\nu_{ei}}{\omega_0}(p_e - p_i).$$

To calculate the electrostatic potential we use the equation for the generaliz ed vorticity, which includes both electric drift and the ion diamagnetic drift, as well as density fluctuation. It results in the appearance additional nonlinear terms H_{NL} in eq. (1):

$$H_{NL} = \frac{\rho^2}{2}\left[\nabla_\perp^2\{\phi, p_i\} - \{\phi, \nabla_\perp^2 p_i\} + \{p_i, \nabla_\perp^2\phi\} + \{V_E^2, n\}\right] \qquad (7)$$

The following variable substitution was used to get eqs. (1)-(6) in presented dimensionless form:

$$t \to t/t_*, \qquad (x, y) \to (x/d, y/d), \qquad \phi \to e\phi/T_*,$$

$$n \to n/n_*, \quad p_{e,i} \to p_{e,i}/p_*, \quad k_y \to k_y\cdot d, \quad \rho = \rho_s/d, \quad \omega_0 = \rho^2\omega_{ci},$$

where $t_* = \frac{1}{\omega_0}$, $\rho_S = \frac{V_*}{\omega_{ci}}$, $V_* = \sqrt{\frac{T_*}{m_i}}$, $\omega_{ce,i} = \frac{eB}{m_{e,i}c}$, $\eta = \frac{m_e\nu_{ei}}{2e^2N_0}$, $p_* = n_*T_*$, $x = (r-r_0)$, $d = a-r_0$ - is the width of the computation region, r_0 - its inner boundary. The normalizing values for density and electron temperature were taken to be $n_* = 10^{13}$ cm^{-3} and $T_* = 350$ eV.

Developed numerical code used a quasispectral decomposition based on the Galerk in method in a single helicity mode approximation ($m/n=q_{res}$ =const), which reduces 3D to 2D the problem, so leads to substantial decrease of the computation time.

Averaging of vorticity equation (1) over the poloidal coordinate *y* gives finally the following dimensionless equation for the evolution of poloidal momentum $G_{0y}=N_0U_{0y}$ [3]:

$$\frac{\partial G_{0y}}{\partial t} + \frac{\partial R}{\partial x} = \nu_0\frac{\partial^2 G_{0y}}{\partial x^2} - \nu_{neo}(G_{0y} - G_{neo}) - \nu_{cx}G_{0y}, \qquad (8)$$

where $R = \rho < V_{Ex}(N_0V_{Ey} + \frac{dp_i}{dx}) > -V_E\Gamma$ - turbulent Reynolds stress, $\rho = \frac{\rho_i}{d}$, $\Gamma = < n_e * V_{Ex} >$, *x* corresponds to radial coordinate.

Note that taking into account new nonlinear terms H_{NL} in vorticity equation (1) results in the appearance of additional term $<V_{Ex}*dp_i/dx>$ in turbulent Reynolds stress tensor, which plays an important role in numerical computation. Equation for electric field is following from ion radial force balance:

$$\frac{cE_r}{BV_*} = V_E = -U_{0y} + V_{pi}, \qquad (9)$$

$$V_{pi} = \frac{\rho}{N_0}\frac{dp_i}{dx} < 0. \ \Phi(x) = \int_x^1 E(x)dx, \quad \Phi(1) = 0$$

Numerical simulations were carried out for the edge region r_0=26 cm < r < 30 cm=a of the T-10 tokamak for the following parameters: R=150 cm, a=30 cm, d=4 cm, B=2.31 T, q_{res}=3, $N_0(r_0)$ =1.6x10^{13} cm^{-3}, $N_0(a)$=0.2x10^{13} cm^{-3}, $T_i(r_0)$=80 eV, $T_i(a)$=12 eV. The choice of the resonant helical modes obeyed to rule m=3*k, k=1, 2, .., K_{max}; K_{max}= < 30. The radial extent of the calculation layer was limited due to the single helicity approach. Increase of electron temperature $T_e(r_0)$ on the inner boundary of the calculation layer was used to simulate transition from OH regime to ECRH regime with various level of input EC-power.

Numerical results show the negative electric potential in the OH regime, $T_e(r_0)^{OH}$ = 60 eV. The gradual increase of the boundary electron temperature $T_e(r_0)^{ECRH}$ = 90, 120, 150 eV leads to corresponding decrease of the absolute value of the electric potential, as shown in Fig. 1. Poloidal velocity U_{0y} is shown in Fig. 2. The value of electric potential and mean E_r shows qualitative agreement with experimental data from Ohmic and ECR heating [4]. Dependence of E_r averaged over the calculation layer on the boundary electron temperature $T_e(r_0)$ is shown in Fig.3. It shows that transition from low $T_e(r_0)$ (OH) to higher $T_e(r_0)$ (ECRH) results in decrease of the absolute value of electric field $|E_r|^{ECRH} < |E_r|^{OH}$, remaining its negative sign.

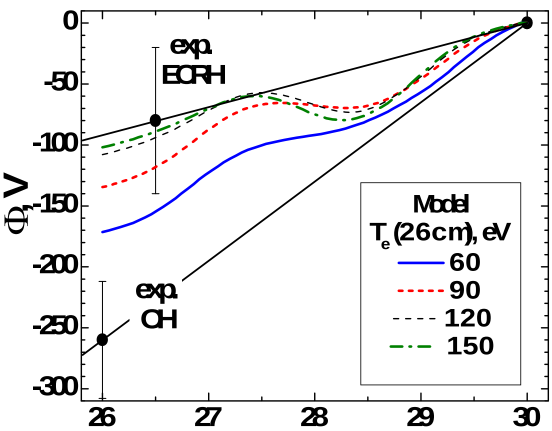

Fig.1

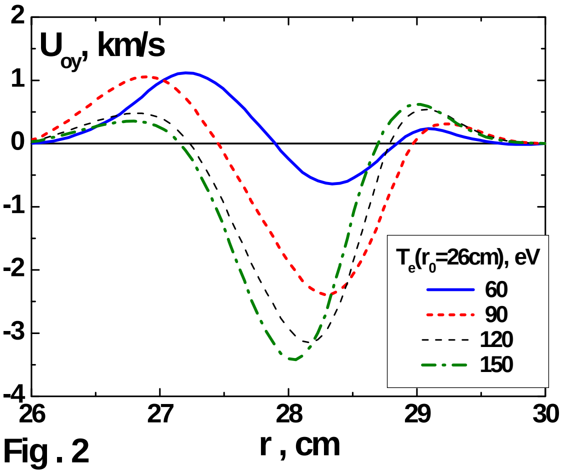

Fig.2

Analysis of numerical calculations shows, that heating of electrons in the edge region leads to some decrease of the mean amplitude of fluctuations due to the increase of longitudinal dissipation ~ $T_e^{3/2}$. On the other hand, it results in recovery of the phase relations between different modes of electrostatic potential, which in turn leads to the increase of the turbulent Reynolds stress in spite of some decrease of fluctuations amplitude. As a result, the absolute value of poloidal velocity U_{0y} increases, see Fig.2. Since $U_{0y} < 0$ and $V_{pi} < 0$, then as follows from equation (9), absolute value of radial electric field decreases with growth $|U_{oy}|$, see Fig. 3. Thus, the computation results qualitatively agree with experimental data.

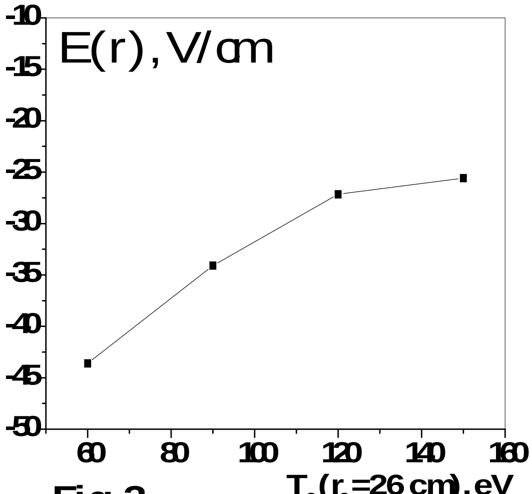

Fig.3

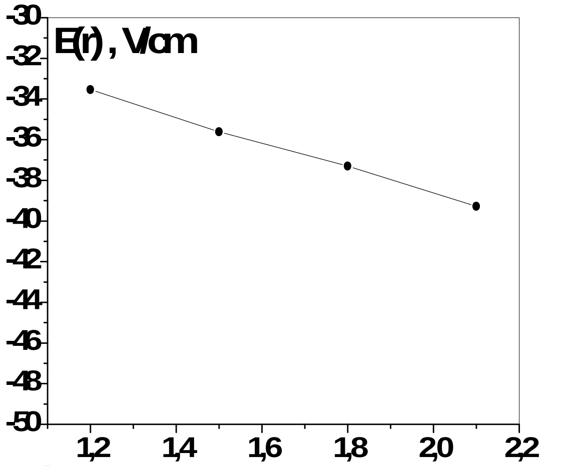

Fig. 4

Dependence of mean electric field on plasma density was also modelled for the same plasma parameters. Plasma density at the inner boundary was chosen to be the only varied parameter for numerical simulations. Calculation was made for the realistic values of $N_0(r_0)$ =1.2 - 2.1x10^{13} cm^{-3}. Figure 4 shows the inverse dependence of modeled electric field on plasma density, which agrees with the tendency, observed experimentally [2].

In summary, the model for the E_r calculation based on the Braginskii's hydrodynamics was developed for the periphery of the tokamak plasma. Numerical results for T-10 conditions show qualitative agreement with direct experimental data, obtained by HIBP. Moreover, the experimental dependences of E_r on plasma temperature and density were obtained by modeling. So, E_r in the strong turbulent plasma of the tokamak periphery was satisfactory described by developed model.

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