Influence of $q(r)$-profile and ECR heating on pressure and density profiles in simulations of tokamak core plasma turbulence

V.P. Pastukhov, D.V. Smirnov

NRC "Kurchatov Institute", Moscow, Russian Federation

The paper continues our previous theoretical study [1–4] of low-frequency (LF) turbulence and the associated cross-field anomalous plasma transport in tokamak core in various regimes of plasma confinement and heating. As it has been discussed earlier, we suggest and apply a relatively simple adiabatically-reduced MHD-like model of nonlinear plasma convection. The model assumes that the plasma is self-consistently maintained near a turbulent-relaxed state (turbulent equipartition state), which is marginally-stable (MS) against the ideal interchange pressure-driven mode. Here we briefly remind the basic principles of our turbulent model. The MS-state is determined by the condition $S = pU^{\gamma} =$ const, where $p = n(T_e + T_i)$ is the total plasma pressure; $U(\psi) = dV(\psi)/2\pi\, d\psi = \oint dl/B_p$ is the specific flux-tube volume; γ is the adiabatic exponent, which specifies the plasma compressibility. The poloidal magnetic flux ψ and the toroidal angle φ are used as the flux coordinates; S is a single-valued function of plasma entropy in the specific flux-tube volume U. The basic set of the adiabatically-reduced equations was derived for axisymmetric toroidal configurations with purely poloidal magnetic field and nested magnetic surfaces [5] assuming that the deviation from the MS-state is small as ε^2, where the parameter of adiabaticity is defined as $\varepsilon^3 \sim \chi / c_s a << 1$ and χ is a background local thermal diffusivity. The crucial element of the model is the adiabatic velocity field:

$$\mathbf{v}_a = \frac{c}{B_p^2}[\mathbf{B}_p \times \nabla\Phi(t,\psi,\varphi)] + c\mathbf{B}_p \lambda \partial_\varphi \Phi(t,\psi,\varphi) \ , \tag{1}$$

which describes a flute-like plasma convection and does not excite the "fast" (high-frequency) stable magnetosonic and Alfvén waves. As it was discussed in [1–3], transition to tokamak configuration approximately corresponds to the following transform in Eq. (1): $\mathbf{B}_p \Rightarrow \mathbf{B} = \mathbf{B}_T + \mathbf{B}_p$ and $\Phi(t,\psi,\varphi) \Rightarrow \Phi(t,\psi,(\varphi - q(\psi)\theta))$, where $q(\psi)$ is the safety factor. It is seen that the transform does not change the radial (normal to the surface) component of the modified $\mathbf{v}_a$:

$$\mathbf{v}_a \cdot \nabla\psi = \frac{c}{B^2}[\mathbf{B} \times \nabla\Phi(t,\psi,(\varphi - q(\psi)\theta))] \cdot \nabla\psi = -c\partial_\varphi \Phi(t,\psi,(\varphi - q(\psi)\theta)) \ . \tag{2}$$

For tokamak simulations it is reasonable to choose γ =2. The set of the reduced equations includes adiabatic equation of motion:

$$\partial_t\big|_\psi \hat{w} + [\Phi, \hat{w}] - \frac{1}{2}[\hat{\rho}, \langle v_a^2 \rangle] + \frac{1}{U^2}\partial_\psi U \partial_\varphi S = \{DT\}_w \;, \qquad [\Phi, \hat{w}] \equiv \partial_\varphi \Phi \partial_\psi \hat{w} - \partial_\psi \Phi \partial_\varphi \hat{w} \;, \quad (3)$$

which is written for the canonical momentum of adiabatic motion called as dynamic vorticity:

$$\hat{w} = \partial_\psi (\hat{\rho} \langle R^2 \rangle \partial_\psi \Phi) + \partial_\varphi \left(\hat{\rho} \left\langle \frac{1}{R^2 B^2} + \lambda^2 B^2 \right\rangle \partial_\varphi \Phi \right). \quad (4)$$

Here $\langle \ldots \rangle$ denotes flux-tube averaging, expression for factor λ is given in [5]. Equations for the entropy function $S = \langle p \rangle U^2$ and plasma mass $\hat{\rho} = \langle \rho \rangle U$ in the flux-tube takes the form:

$$\partial_t\big|_\psi S + [\Phi, S] = \{DT\}_S \;, \qquad \partial_t\big|_\psi \hat{\rho} + [\Phi, \hat{\rho}] = \{DT\}_\rho \;, \quad (5)$$

where $\{DT\}_w$, $\{DT\}_S$ and $\{DT\}_\rho$ in the right-hand-sides of Eq. (3), (5) denotes dissipative terms, which includes background kinematic viscosity η, thermal diffusivity χ, resistive diffusion, as well as energy, momentum, and particle sources. The mechanism of anomalous transport is based on a competition between the dissipative and the ideal processes. In this case the plasma heating and the background thermal conductivity distort the initial pressure profile making it a weakly unstable, while the instability induces and maintains the quasi-2D nonlinear convection, which tends to restore the MS pressure profile and results in the anomalous non-diffusive cross-field plasma transport.

Similarly to the experimental data obtained in various tokamaks [6-9], the turbulence in our simulations [1-4] demonstrates the tendency to maintain the self-consistent pressure profiles $p(t,r)$, which normalized shapes are almost unchangeable in time. The first set of the simulation runs presented here were performed to analyze how different $q(r)$-profiles influence the pressure profile formation in the simulations of turbulent tokamak plasmas. Fig. 1a shows pressure profiles obtained in simulations those are performed for the parameters of OH shots #39562, #33389, #22888 with different safety factors q_L at the limiter in tokamak T-10. These shots are discussed in Sec. 3 of Ref. [7]. According to [7], as well as to Ref. [8, 9], which also discuss results from some other tokamaks, the pressure profiles in regimes with different q_L been expressed in terms of dimensionless minor radius $\rho = r \big/ \sqrt{I_p R / B}$ have a rather universal shape. Here I_p, R, and B are the total plasma current, the major radius, and the toroidal magnetic field expressed in amperes, cm, and gauss respectively. Fig. 1b shows the

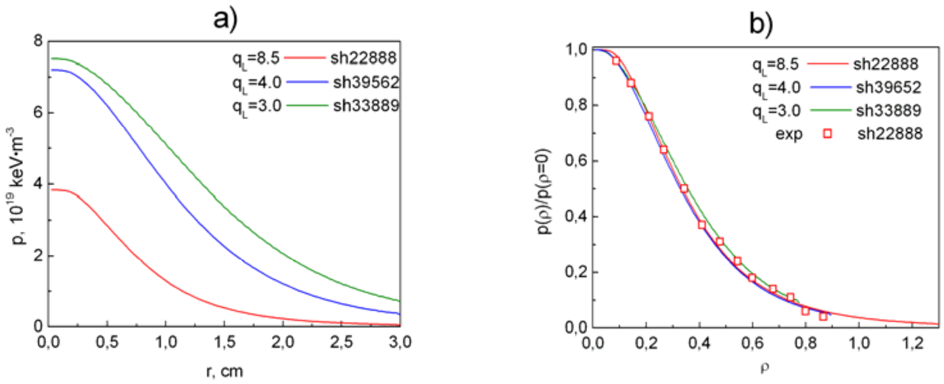

Fig.1. Radial profiles of plasma pressure in simulations of T-10 discharges with different q_L: a) real pressure profiles; b) normalized pressure profiles as functions of normalized radius ρ. Boxes correspond to experiment.

pressure profiles from the simulations and from the experiment as functions of the normalized radius ρ. It is seen that the pressure profiles obtained in our simulations for OH regimes with different q_L demonstrate the self-consistent shape in terms of the dimensionless minor radius ρ and the rather good agreement with the experimental results.

The second set of the simulation runs were performed in connection with the "density pump out" effect observed in many tokamak experiments with ECRH. A quite reasonable qualitative interpretation of this effect was presented in papers [6,8,9]. It is based on numerous of experiments in which temperature profiles have an appreciable peaking after the central ECRH switching-on while the pressure profiles approximately conserve their self-consistent form (see, for example, Fig. 2 in [6]). As a result, the density profiles demonstrate flattening and even formation of density depression in the plasma core. Our model of turbulent convection also demonstrates the tendency to maintain the self-consistent pressure profiles, which have the physical sense of turbulent-relaxed (turbulent equipartition) states. The tendency is rather strong, because any picking or steepening of these pressure profiles results in a fast enhancement of the turbulence. The turbulent convection also demonstrates the tendency to maintain the corresponding turbulent-relaxed profiles for density and temperature. However, deviations from these profiles do not lead to the turbulence enhancement, if the pressure profile is still unchanged. Thus, our turbulent model does not contradict to the qualitative interpretation of the density pump out effect. Therefore, we have tried to initiate this effect in our simulations. Unfortunately, simple switching-on of the central ECRH has shown very weak modification of the initial density profiles in our simulations [4] that cannot be considered as the density pump out. Accompanying the ECRH switching-on by an enhancement of particle sourse at the edge (imitation of "gas puffing") we have obtained the formation of flat or non-monotonic density profiles near the axis [4]. However, this effect is rather a reduction of "density pinch" than the "density pump out".

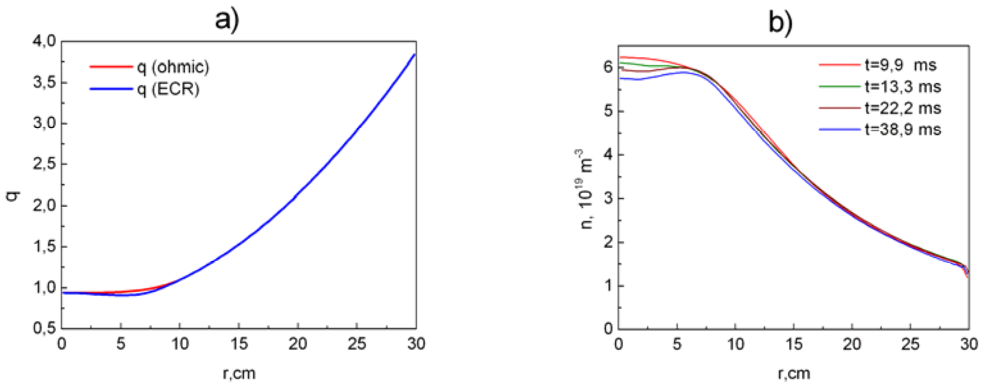

Fig.2. a) modification of *q(r)* profile after the ECRH switching-on; b) evolution of plasma density profile.

To enhance the effect of density reduction in the plasma core after the ECRH switching-on we have performed simulations, in which initial *q(r)*-profile transforms to a weakly non-monotonic profile after the ECRH switching-on. An initial stage of the simulation run corresponds to OH regime with typical T-10 parameters during which the turbulence and the transport processes come to a quasi-steady state. Central ECRH is turned on in the moment *t*=11ms. Then we assume that after this moment the *q(r)*-profile starts modification with characteristic time ~10ms from monotonic shape *q(ohmic)* to a slightly non-monotonic profile *q(ECR)* as shown at Fig. 2a. Density profile evolution is shown at Fig. 2b. The simulations demonstrate that very small (<3%) modifications of the *q(r)*-profile near the axis can lead to the formation of an appreciable (~10%) density depression in the plasma core.

The work is supported by grant No. 4361.2012.2 of President of Russian Federation for Leading Scientific Schools.

References

[1] V.P. Pastukhov and N.V. Chudin, JETP Letters 90, 651 (2009)

[2] V.P. Pastukhov and N.V. Chudin, 23nd IAEA Fusion Energy Conference, Daejeon, Republic of Korea, 2010, Report THC/P4-22

[3] V.P. Pastukhov, N.V. Chudin, and D.V. Smirnov, Plasma Phys. Control. Fusion 53, 054015 (2011)

[4] V.P. Pastukhov, N.V. Chudin, and D.V. Smirnov, 38 EPS Conference on Plasma Physics, Strasbourg, France, 2011, Report P4.136

[5] V.P. Pastukhov, Plasma Phys. Reports 31, 577 (2005)

[6] K.A. Razumova, *et al*, Plasma Phys. Control. Fusion 48, 1373 (2006)

[7] K.A. Razumova, *et al*, Plasma Phys. Control. Fusion 50, 105004 (2008)

[8] K.A. Razumova, *et al*, Nucl. Fusion 49, 065011 (2009)

[9] K.A. Razumova, *et al*, Nucl. Fusion 51, 083024 (2011)