Evolution of turbulent transport and plasma energy confinement time in tokamaks in regimes with additional heating: simulations and comparison with T-10 experiments

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The paper continues our previous theoretical study [1-4] of low-frequency (LF) turbulent convection and the resulting anomalous cross-field transport in tokamak core plasmas in various quasi-steady and transient regimes of plasma confinement and heating. Relatively simple adiabatically-reduced MHD-like model of nonlinear plasma convection has been proposed and used in our simulations. The total (anomalous) radial magnetic-surface-averaged heat fluxes both for electron and ion components consist of background and turbulent parts: $q_{(e,i)}^{tot} = q_{(e,i)}^{bg} + q_{(e,i)}^{turb}$. Similarly the surface-averaged particle flux $\mathit{\Gamma}_{\mathrm{tot}}$ also consists of background and turbulent fluxes: $\mathit{\Gamma}_{\mathrm{tot}} = \mathit{\Gamma}_{\mathrm{bg}} + \mathit{\Gamma}_{\mathrm{turb}}$. Typically, we associate the background fluxes with some kind of neoclassical diffusive fluxes. Contrary to the background fluxes the turbulent fluxes are non-diffusive and are calculated using the direct self-consistent solution of nonlinear equations for fluctuations of turbulent velocity, pressure, and density as it described in papers [1, 2]. Similarly to the transport code ASTRA [5], the magnetic surfaces are marked by the effective minor radius $\rho = \sqrt{\Psi / \pi B_0}$, which depends on toroidal magnetic flux Ψ and is invariant to the magnetic surface shape.

The global plasma energy confinement time τ_E is sensitive to an appropriate choice of boundary conditions for the heat fluxes at the external boundary between main plasma volume and SOL at $\rho = a$. In general, the particle and heat fluxes have to be continues at $\rho = a$, however, we don't solve the transport problem in SOL. We can only mention that the main plasma losses in SOL are along the field-lines and, therefore, heat flux from the SOL has to be proportional to volume-averaged thermal energy in SOL. Further, due to relatively small thermal capacity of the SOL region, the heat flux, escaping from the SOL, has to be approximately equal to the heat flux, incoming into the SOL from the main plasma. We can also assume that the volume-averaged thermal energy in SOL is proportional to plasma pressure at the boundary surface $\rho = a$. Taking into account the above arguments, we can finally write the following generalized third type external boundary conditions for the heat fluxes:

$$q_{(e,i)}^{tot}\Big|_{\rho=a} = \nu_E V n T_{(e,i)}\Big|_{\rho=a}, \tag{1}$$

where n and $T_{(e,i)}$ are plasma density and temperatures, V is main plasma volume, and ν_E is a coefficient that characterizes the plasma energy confinement in SOL.

In our previous simulations we assumed that ν_E = const and chose it value to provide the same plasma energy confinement time τ_E at the initial quasi-steady stage of the simulation run as in the corresponding experimental shot. However, only small decrease of final steady-state τ_E was seen when the additional plasma heating was turned on in the case ν_E = const, while the tokamak experiments typically demonstrate a rather strong decrease of τ_E, when the total plasma heating power $Q_E = \int(P_e+P_i)dV$ is increased:

$$\tau_E \equiv 3V\langle n(T_e+T_i)\rangle/2Q_E \propto (Q_E)^{-\alpha}\ . \tag{2}$$

The above relation can be also written as the dependence of τ_E on the volume-averaged plasma thermal energy density: $\tau_E \propto \langle n(T_e+T_i)\rangle^{-\alpha/(1-\alpha)}$. In this paper we show that the above steady-state power scaling (2) for the τ_E can be achieved in simulations with non-linear third type boundary conditions, in which the coefficient ν_E depends on n and $T_{(e,i)}$ at $\rho = a$. Our previous simulations have shown that the LF turbulence maintains self-consistent plasma pressure profiles, which shape is in a good agreement with the pressure profiles observed in many tokamak experiments [6-9]. Due to this circumstance we assume that the plasma pressure $n(T_e+T_i)\big|_{\rho=a}$ at the external boundary is maintained approximately proportional to the volume averaged pressure in the core $\langle n(T_e+T_i)\rangle$ and propose the non-linear third type boundary conditions (1), in which ν_E depends on the local time-dependent values of plasma density n and temperatures $T_{(e,i)}$ at the external plasma boundary. As in previous simulations, the boundary conditions for the turbulent velocities were chosen to provide zero external flux of plasma kinetic energy, therefore, $(q_e^{tot}+q_i^{tot})\big|_{\rho=a} = Q_E$ in steady states. All simulation runs start from quasi-steady OH stages, after which heating pulses with various power inputs are switched on. In this case the outgoing heat fluxes in (1) can be written as follows:

$$q_e^{tot} = Q_{OH}\,\frac{nT_e}{n(T_e+T_i)_{OH}}\left(\frac{n(T_e+T_i)}{n(T_e+T_i)_{OH}}\right)^{\frac{\alpha}{1-\alpha}}\Bigg|_{\rho=a},\quad q_i^{tot} = Q_{OH}\,\frac{nT_i}{n(T_e+T_i)_{OH}}\left(\frac{n(T_e+T_i)}{n(T_e+T_i)_{OH}}\right)^{\frac{\alpha}{1-\alpha}}\Bigg|_{\rho=a} \tag{3}$$

Simulations of plasma turbulence and anomalous transport with the boundary conditions (3) were performed using CONTRA-C code (cylindrical model of tokamak with circular

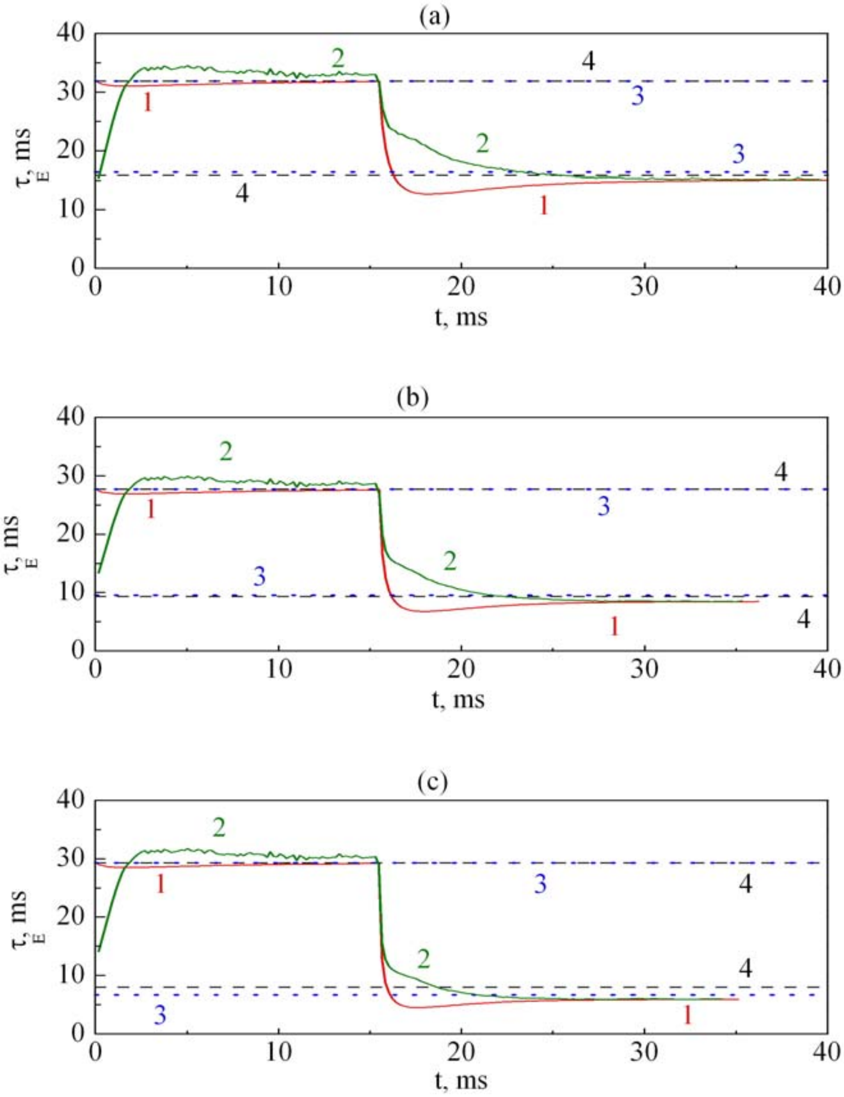

Fig.1. Evolution of plasma energy confinement time τ_E for parameters of three shots in tokamak T-10: (a) – shot #61203, (b) - shot #61200, (c) – shot #61208. Curve 1 (red line) shows evolution of $\tau_{E(st)}$ in steady-state definition; curve 2 (green line) shows evolution of $\tau_{E(tr)}$ in transient definition; lines 3 (blue dotted lines) show steady τ_E levels those correspond to power scaling Eq. (2) with $\alpha = 0.69$ for initial (OH) and final (ECRH) stages; lines 4 (black dashed lines) show steady OH and ECRH levels of τ_E in the experimental shots.

plasma cross-section and joint heat transport equation for electrons and ions with fixed T_e/T_i ratio). Fig.1 demonstrates the evolution of plasma energy confinement time τ_E in simulations those correspond to parameters of three shots in tokamak T-10 discussed in paper [8]. All simulation runs start from the OH quasi-steady stages those last 15ms. Then the ECRH power was switched on with the rise time about 1ms. The total plasma heating power Q_E increased 2.6 times after the ECRH power switching on in shot #61203, 4.6 times in shot #61200, and 8.23 times in shot #61208. We use two definitions of τ_E. The first one is steady-state definition $\tau_{E(st)} = 3V\langle n(T_e+T_i)\rangle/2Q_E$ that corresponds to Eq. (2). The second definition of $\tau_{E(tr)}$ corresponds to transients and follows from the power-balance equation:

$$\frac{d}{dt}\left(\frac{3}{2}\langle n(T_e+T_i)\rangle\right)=Q_E-\frac{3\langle n(T_e+T_i)\rangle}{2\tau_{E(tr)}}. \quad (4)$$

Evolutions of $\tau_{E(st)}$ and $\tau_{E(tr)}$ are shown in Fig.1 by curves 1 and 2. The simulations are performed for exponent $\alpha = 0.69$ that corresponds to ITER H-mode scaling (ITER-98(y,2)). Lines 3 correspond to this scaling and show expected levels of τ_E in the initial (OH) and final (ECRH) steady-states. Lines 4 show experimental values of τ_E in the OH and the ECRH steady-states. Simulations for all three shots with essentially different ECRH power input demonstrate asymptotic approaching of $\tau_{E(st)}$ and $\tau_{E(tr)}$ to the expected scaling levels, as well as to the experimental τ_E in steady-states.

Thus, we have shown that the decrease of τ_E with the power input enhancement can be associated with plasma losses in SOL (at least in our model of turbulence). Let us try to estimate roughly a physical mechanism which could be responsible for the plasma losses in SOL. We can assume that the main energy losses in SOL are defined by heat conduction along the field lines (with a fixed connection length). The classical heat conductivity is proportional to $v_{Te}^2\tau_{ee} \propto T_e^{5/2}$ that gives the following relation for the exponent α: $\alpha/(1-\alpha) = 5/2$ or $\alpha \approx 0.71$. This value is very close to $\alpha = 0.69$ used above.

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