Simulations of self-sustained turbulent convection and formation of ITB in tokamak core plasmas

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Introduction

• the paper continues our previous theoretical study of anomalous cross-field transport in tokamak core plasmas (PPCF 53, 054015 (2011), Plasma Phys. Reports, 43, 405 (2017). and others);

• the study is based on direct dynamic simulations of self-consistent low-frequency (LF) turbulent convection and the associated cross-field plasma transport;

• relatively simple adiabatically-reduced MHD-like model of nonlinear plasma convection is used in our simulations;

• in this report we present a modification of the model which allows us to create conditions for a formation of transport barriers near the major resonant magnetic surfaces (RMS);

• the first set of simulations were performed using CONTRA-C code (cylindrical geometry) for transient regimes with ECR heating and ITB formation in T-10;

• the second set of simulations were performed for conditions of T-15MD with non-circular plasma cross-section using transport code ASTRA with turbulent block CONTRA-A
Basic model of nonlinear turbulent plasma convection and transport fluxes

• general principles of the proposed turbulent transport model were discussed earlier in JETP Letters, 82, 356 (2005), Plasma Phys. Reports, 31, 577 (2005), application to tokamak was discussed in JETP Letters, 90, 651 (2009), PPCF, 53, 054015(2011); Plasma Phys. Reports, 43, 405 (2017).

• the main equations of the adiabatically-reduced plasma convection model are written in terms of more appropriate variables:

  effective minor radius \[ \rho = \sqrt{\Psi / \pi B_0} \]

  entropy functions, averaged over flux-tube volume \( U \):

  \[ S_{e,i} = p_{e,i} U^2 = \overline{S}_{e,i} (t, \rho) + \tilde{S}_{e,i} (t, \rho, \varphi) \]

  number of plasma particles in the flux-tube volume:

  \[ D = nU = \overline{D}(t, \rho) + \tilde{D}(t, \rho, \varphi) \]
• the equation for the particle transport has the standard form;

• the heat transport equations for electrons and ions take into account the empirical value $\gamma = 2$ for the adiabatic exponent, which provides better agreement with tokamak experiments including the effect of the pressure profile consistency;

• the equations for the heat transport are modified to the more conservative form:

$$
\frac{3}{2} \frac{U}{V'} \partial_t (\overline{nT_{(e,i)}} V'^2) + \partial_{\rho} (Uq_{(e,i)}^{\text{turb}} + Uq_{(e,i)}^{\text{bg}} + 3UT_{(e,i)} \Gamma_{bg}) = V'U (\overline{P_{(e,i)}} + \overline{P_{c(e,i)}})
$$

where the "background" heat fluxes $q_{(e,i)}^{\text{bg}}$ are taken in the version of the Chang-Hinton, $V' \equiv \partial_{\rho} V$ and the turbulent fluxes of heat and particles are specified by the following expression:

$$
q_{(e,i)}^{\text{turb}} = -2\pi c \sum_{n=1}^{n_{\text{max}}} \left( \overline{S_{n(e,i)} \partial_{\phi} \phi_n} \right) / U , \quad \Gamma_{\text{turb}} = -2\pi c \sum_{n=1}^{n_{\text{max}}} \left( \overline{D_n \partial_{\phi} \phi_n} \right)
$$
Motivation

- All turbulent fluctuations in tokamaks can be decomposed into harmonics of toroidal and poloidal angles $\varphi$ and $\theta$.

- The main influence of the magnetic shear in tokamaks results from two features:
  1. $(m,n)$-harmonics of fluctuations are localized near RMS where $q(\rho) = m/n$, however, due to partial overlapping and toroidal and/or nonlinear coupling of the harmonics with succeeding $m$-numbers can form linked radially extended chains.

![Graph showing rational surfaces and transport coefficient distribution](image)
2 – there are enhanced intervals ("gaps") between RMS $q(\rho) = m/n$ with moderate $n$-numbers and the major RMS with integer and half-integer values of $q(\rho)$.

Figure shows the profile of safety factor $q(\rho)$ and the radial distribution of the RMS with toroidal numbers $n \leq 20$ for one of the planned basic scenarios in tokamak T-15MD.
Experimental evidence of multy-barrier pressure profiles

Modified model of nonlinear turbulent plasma convection

- simplified model of LF plasma turbulence, in its basic form, does not account the discreteness of the poloidal $m$ numbers. Therefore, the radial size is restricted only by boundary conditions at $\rho = 0$ and at the outer boundary with SOL;

- we introduce intermediate boundary conditions for harmonics with moderate toroidal $n$-numbers $0 < n \leq n_b \leq n_{\text{max}}$ in the “gaps” near the major RMS: $S_{n(e,i)} = 0$, $D_n = 0$ and are continues in 2 points at both sides of the major RMS;

- functions $w$ and $\phi$ strongly depend of each other due to the equation:

$$w = \frac{1}{3} 10^{-4} \left[ \frac{h}{\rho} \partial_\rho \left\{ f_1 (D_0 + D_f) \frac{h}{\rho} \partial_\rho \phi \right\} + (f_3 + f_4) \partial_\phi \left\{ (D_0 + D_f) \right\} \partial_\phi \phi \right]$$

where $\phi$ expressed in keV, the number of particles $D$ in the specific volume is expressed in units of $10^{19} (T \cdot m^2)^{-1}$, and $h$, $f_1$, $f_3$ and $f_4$ are the form factors in SI units.
Therefore, $\phi_n(\rho) = 0$ and is continues together with the continuity of $\phi_n'(\rho)$ in the intermediate boundary points, while $w_n(\rho)$ is only continues, but not smooth in these boundary points;

- as it was discussed in our previous papers, at the external boundary with SOL we assume the generalized nonlinear boundary conditions of third kind for the electron and ion heat fluxes that provides the scaling $\tau_{E(st)} \propto (Q_E)^{-\alpha}$, where $Q_E = \int (P_e + P_i) dV$ is the total heating power;

- below we use both “steady state” and “transient” definitions for $\tau_E$:

$$\tau_{E(st)} \equiv 3V \left\langle n(T_e + T_i) \right\rangle / 2Q_E$$

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

- in these simulations we assume the parameter $\alpha = 0.69$ in the external nonlinear boundary conditions that corresponds to scaling ITER-98(y,2) for $\tau_{E(st)}$
Radial profiles of the main parameters of turbulent plasma in T-10 in the scenario with intermediate boundary conditions in the vicinity of 5 RMSs \( q(\rho) = 1; 3/2; 2; 5/2; 3 \).

The left column presents profiles at the OH stage; the middle column presents profiles at the steady stage of central ECRH; the right column presents profiles at the steady stage of non-central ECRH.
Evolution of the plasma parameters in T-15MD in scenario with NBI and central ECRH

Influence of the intermediate boundary conditions in the vicinity of RMSs
\[ q(\rho) = 1; 2 \text{ and } 3. \]

1. After the OH stage at the moment \( t_1 = 0.05s \) 8MW of NBI is turned on.

2. Additional 5MW of central ECRH is turned on at the moment \( t_2 = 0.12s. \)
Typical 2D-structures of well-developed turbulent fluctuations of plasma potential $\phi(r,z)$, dynamic vorticity $w(r,z)$, electron and ion pressures $p(r,z)$ in poloidal plasma cross-section in the simulations for T-15MD with 3 ITBs.

\[
\phi_t(r,z) = \text{const}
\]

\[
p_{et}(r,z) = \text{const}
\]

\[
w_t(r,z) = \text{const}
\]

\[
p_{it}(r,z) = \text{const}
\]
Radial profiles of the main parameters in T-15MD in scenario with NBI and central ECRH in the presence of the intermediate boundary conditions in the vicinity of RMSs $q(\rho) = 1; 2 \text{ and } 3$. 
Summary

• simulations of self-consistent LF turbulent convection with the non-linear third type boundary conditions and the additional intermediate boundary conditions near the major RMSs for harmonics with $0 < n \leq n_b$ have demonstrated the formation of ITBs;

• levels of the fluctuations are reduced approximately 10 times in comparison with the fluctuation levels in our previous simulations without the additional boundary conditions both for T-10 and T-15MD;

• the radial layers with a large “shear” of toroidal plasma rotation (more precisely, with the high dynamic vorticity of the toroidal plasma rotation) can be formed near the major RMS. However, contrary to the popular belief, they are not the root cause of the ITB formation, but rather are the consequence of modified plasma convection near the major RMS;