L-H TRANSITION SIMULATIONS
BASED ON EDGE TURBULENT LAYER MODEL

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1. Introduction

Based on Edge Turbulent Layer model (ETL-model [1]) the combined ASTRA-ETL numerical code has been developed, which is able to describe the phenomenon of transport barrier formation just within the separatrix during the L-H transition in tokamak. It is shown that four-field set of Braginskii hydrodynamic equations describing edge fluctuations of electron and ion temperatures, density and potential can be reduced to three Lorenz-like set of equations coupled through the equation for the kinetic energy of the fluctuations - the four-field ETL-model, which describes the nonlinear dynamics of the convective cells in presence of the sheared flow. For a given T_{Be} , T_{Bi} and n_B at the inner boundary of the turbulent layer (TL) and fixed T_{Se} , T_{Si} and n_S at the separatrix the ETL-model permits to calculate ion and electron heat and particle fluxes through the separatrix. These fluxes are used as a boundary condition of the third kind for the profile calculations in the bulk plasma done by ASTRA code. At the TL boundary $R=R_B$: $-D_a^{ASTRA}\cdot\frac{\partial f_a}{\partial r}=\Gamma_a^{ETL}$, where f_a means T_e , T_i and n, D_a^{ASTRA} means corresponding heat and particle diffusivities in L-mode, and Γ_a^{ETL} means the values of the electron and ion heat and particle fluxes calculated by the ETL model for the values of the T_{Be} , T_{Bi} and n_B found by ASTRA from the profile calculations at the previous time step. Numerical modelling results and analytic estimates lead to the conclusion that both the first threshold of plasma pressure gradient for the onset of the L-mode turbulence and the second one for the sheared flow generation and turbulence stabilization in H-mode appear to be lower than in the case when only one kind of fluctuations is considered. Comparison with the experimentally measured turbulent fluctuations in DIII-D manifests strong dependence of the L-H transition power on separatrix values T_{eS}, T_{iS} and n_S.

2. Four-field etl-model

Four-field ETL-model is derived from the reduced Braginskii fluid equations [2] in the electrostatic limit. Because the model is developed to describe the edge turbulent convection perpendicular to the magnetic field, the equation for ion parallel velocity is omitted for simplicity. Ion and electron temperatures are treated separately, because their difference seems important for the L-H transition power threshold value. The normalized, nonlinear equations for drift-resistive-ballooning instability-induced turbulence are [3]:

$$\frac{\partial\Delta\varphi}{\partial t}+[\vec{e}_z\times\nabla\varphi]\nabla\Delta\varphi+g_B\frac{\partial n(T_i+T_e)}{\partial y}=\sigma(\tilde{\varphi}-\alpha\tilde{T}_e-\tilde{n})+\mu\Delta^2\varphi, \qquad (1)$$

$$\frac{\partial n}{\partial t}+[\vec{e}_z\times\nabla\varphi]\nabla n+g_N\frac{\partial\varphi}{\partial y}=\sigma(\tilde{\varphi}-\alpha\tilde{T}_e-\tilde{n})+g_B\frac{\partial(n-\varphi)}{\partial y}+D\Delta n, \qquad (2)$$

$$\frac{\partial T_e}{\partial t}+[\vec{e}_z\times\nabla\varphi]\nabla T_e+g_{T_e}\frac{\partial\varphi}{\partial y}=\frac{2}{3}\alpha\sigma(\tilde{\varphi}-\alpha\tilde{T}_e-\tilde{n})+\chi_e\Delta T_e+Q_{ie}, \qquad (3)$$

$$\frac{\partial T_i}{\partial t}+[\vec{e}_z\times\nabla\varphi]\nabla T_i+g_{T_i}\frac{\partial\varphi}{\partial y}=\chi_i\Delta T_i-Q_{ie}, \quad (4)$$

where $\alpha = 1.71$ is constant, φ is the dimensionless electrostatic potential normalized by T_{eS}/e, n is the electron density normalized by n_s, T_e and T_i are the electron and ion temperatures normalized by the electron temperature at the separatrix T_{eS}. . These fluctuating quantities are represented in the form (φ, n, T_e and T_i should be substituted instead of f):

$$f=\langle f\rangle+f_0(x,t)+\tilde{f}(x,y,t),\ \langle f\rangle=(1-x\rho/L)(f_B(t)-f_S)/f_S. \quad (5)$$

x and y corresponding to the radial and poloidal directions (Fig.1) are normalized by Larmor radius $\rho=C_s/\omega_c$, time t is normalized by gyroperiod ω_c^{-1}. $\langle T\rangle$ and $\langle n\rangle$ correspond to the mean dimensionless temperature and density gradients in TL: $g_{Te} = \rho\cdot(T_{eB} - T_{eS})/(L\cdot T_{eS})$, $g_{Ti} = \rho\,(T_{iB}\,T_{iS})/(L\cdot T_{eS})$ and $g_n = \rho\cdot(n_B - n_S)/(L\cdot n_S)$, $g_B = \rho/R_{pl}$ is the normalized reversed magnetic field curvature radius at the outboard side of the tokamak; $\sigma = \sqrt{M_i/m_e}\,k_\parallel^2\,\rho\lambda_e$ is proportional to the plasma Spitzer conductivity, $k_\parallel = 1/qR_{pl}$, which implies, that the parallel correlation length in the convective cells is of order of qR_{pl}; λ_e is the electron mean free path, the viscosity μ and the thermal diffusivity χ are normalized by ρC_s.

To reduce the eqs. (1)-(4) to the Lorenz-like set [4], one can follow the procedure used in [1] for the two-field ETL-model. First three Fourier harmonics are taken into account:

$$\varphi=(V/k_x)\sin k_x x+[X_c\cos k_y y+X_s\sin k_y y](1/k_x)\sin k_x x+[\varphi_{2c}\cos k_y y+\varphi_{2s}\sin k_y y]\sin 2k_x x, \quad (6)$$

$$f=-Z\sin 2k_x x+[Y_c\cos k_y y + Y_s\sin k_y y]\sin k_x x +[f_{2s}\sin k_y y +f_{2c}\cos k_y y]\sin 2k_x x. \quad (7)$$

Fourier expansion (7) is the same for T_e , T_i and n, and henceforth the indices e, i and n are introduced for the corresponding amplitudes of the perturbation of the mean profile Z and of the amplitude of turbulent fluctuations Y. The four-field ETL-model equations are written for the integral variables normalized according to

$$V=\frac{cE_r}{C_S B},\ X=\frac{e\varphi_{rms}}{T_{se}}\frac{\pi\rho}{2L},\ Y_i=\frac{T_{irms}}{2T_{se}},\ Y_e=\frac{T_{erms}}{2T_{se}},\ Y_n=\frac{n_{erms}}{2n_{se}},\ f_{rms}=\left(\sum_k|f_k|^2\right)^{1/2}.$$

Notations are kept the same as in Lorenz system in order to see relation with it.

V: $\dot{V}=V_1\cdot X^2\cdot V-V_2\cdot V+V_3$, (8)

$\tilde{V}$: $\dot{X}=-V_1\cdot X\cdot V^2+I_2\cdot[Y_i+Y_e+I_{2n}\cdot Y_n]-I_3\cdot X$, (9)

T_i^0: $\dot{Z}_i=Z_1\cdot X\cdot Y_i-Z_2\cdot|X|\cdot Z_i-Z_{3i}Z_i+\hat{Q}(Z_e-Z_i)$, (10)

$\tilde{T}_i$: $\dot{Y}_i=-J_1\cdot X\cdot Z_i+J_{2i}\cdot X-J_{3i}\cdot Y_i$, (11)

T_e^0: $\dot{Z}_e=Z_1\cdot X\cdot Y_e-Z_2\cdot|X|\cdot Z_e-Z_{3e}Z_e-\hat{Q}(Z_e-Z_i)$, (12)

$\tilde{T}_e$: $\dot{Y}_e=-J_1\cdot X\cdot Z_e+J_{2e}\cdot X-J_{3e}\cdot Y_e$, (13)

n^0: $\dot{Z}_n=Z_1\cdot X\cdot Y_n-Z_2\cdot|X|\cdot Z_n-Z_{3n}Z_n$, (14)

$\tilde{n}$: $\dot{Y}_n=-J_1\cdot X\cdot Z_n+J_{2n}\cdot X-J_{3n}\cdot Y_n$, (15)

where $V_1 = 2.7\cdot 10^{-7}/\mu$, $V_2=(\nu+\nu_{cx})/\omega_c$, $\nu=\frac{\omega_T\cdot\nu_*}{(1+\nu_*)(1+\nu_*\varepsilon^{3/2})}$ is the neoclassical viscosity, $\nu_{cx}=\langle v\sigma\rangle_{cx}n_n$ is the simplest representation of the charge exchange friction between ions and neutrals, when the averaged neutral poloidal flow is assumed to be zero. Here ν_* is the ion collisionality, n_n is the neutral density at the TL. V_3 is a very small source term providing seed velocity necessary to initiate the "peeling" instability, when the sheared flow is generated by the convective cells. $I_2 = g_B/\sqrt{2}$, $I_{2n}=1+T_{Si}/T_{Se}$, $I_3 = (\sigma k^{-2} +\mu k^2)$, $J_1 = k_x/\sqrt{2}$, $J_{2i} = (g_{Ti} - g_B)/\sqrt{2}$, $J_{3i} =\chi_i k^2$. It is assumed that the viscosity and the thermal conductivity are due to the small scale selfsimilar fluctuations, which provide the energy sink at the small scales, so $\mu = \chi = 0.04\ D_B$., where $D_B=\rho C_s/D_B$, $Z_1 = k_x/\sqrt{2}$, $Z_2 = (L/\rho)\ k_x^2$, $Z_{3i} = 4\chi_i k_x^2$, $k_x = k_y = \rho\cdot\pi/L$, $k^2 = k_x^2 + k_y^2$, where L, the TL width, is determined by the balance of the growth rate of the interchange instability and of the dissipation rate due to parallel electron conductivity along the field lines: $\frac{\partial\Delta\varphi}{\partial t} \approx \sigma\varphi$, or $\frac{\pi^2\rho^2\gamma_g\varphi}{L^2\omega_c} \approx \sigma\varphi$, $\gamma_g=C_S/(R_{pl}L)^{0.5}$. For the case of DIII-D parameters in Ohmic L-mode (shot #82830 [5]): R_{pl} = 1.67 m, $a_{pl} = 0.63\,m$, $B = 1.58\,T$, $I_{pl} = 1\,MA$, q=4.51, b_{pl}/a_{pl} = 1.6, $n_S = 1.7\cdot 10^{19}\,m^{-3}, n_B = 3.12\cdot 10^{19}\,m^{-3}$, $T_{Si} = 60\ eV$,

$T_{Se} = 45\,eV$ T_{Bi} = 85 eV, T_{Be} =79 eV (16)

one can obtain $L \approx 1\ cm$, henceforce it is fixed for all simulations. The term Z_2 appears from taking into account the thermal diffusive boundary layer of the width Δ inside the cell. Remind, that the TL consists of the convective cells rotating in alternating directions (Fig. 1). The thermal diffusive boundary layer inside the cell appears because every convective cell drives the convective heat flux: $TV_c\Delta$, which has to percolate diffusivly through the boundary of the cell: $\chi LT/\Delta$, where $V_c=|X|\,C_S$ is the characteristic velocity inside the convective cell, and T is the temperature difference between the sides of the cell. By equalizing the convective and diffusive fluxes one can estimate the boundary layer width $\Delta \propto (\chi L/V_c)^{0.5}$. Then the turbulent diffusive term is given by $\chi k_x^2(\mathrm{L}^2/\Delta^2)=(L/\rho)k_x^2|X| =Z_2|X|$. $Z_{3e}=4\chi_e k_x^2$, $Z_{3n}=4D_i k_x^2$, $J_{2e} = (g_{Te} - g_B)/\sqrt{2}$, $J_{3e} = \frac{2}{3}\alpha^2\sigma + \chi_e k^2$, $J_{2n} = (g_n - g_B)/\sqrt{2}$, $J_{3n} = \sigma + Dk^2$.

3. Discussion of simulations

Time-dependent transport and edge turbulence simulations were carried out for 2.5 MW NBI heated 82830 discharge from DIII-D [5]. The amplitudes of the fluctuations, sheared velocity and heat and particle fluxes were calculated for L-mode (16) and for the ELM-free H-mode:

$n_S = 0.8\cdot 10^{19}\,m^{-3}$, $n_B = 2.4\cdot 10^{19}\,m^{-3}$, T_{Si} =44 eV, T_{Se} =32 eV, T_{Bi}=110 eV, T_{Be}=80 eV. (17)

For the four-field ETL-model the experimental temperature and density gradients in TL were taken from the experiment. For the combined ASTRA-ETL code only separatrix values were taken from the experiment and gradients were calculated selfconsistently. Results of ASTRA-ETL simulations are taken in L-mode at 5 ms before the transition and in stationary H-mode. The comparison with the experiment summarized in the following table shows ≈40% quantitative agreement.

	conf. mode	L_n (mm)	L_{Te} (mm)	n_{rms}/n	$e\varphi_{rms}/T$	Γ ($10^{20}/m^2s$)	V (m/s)
experiment	L	17	18	0.3-0.4	0.15-0.3	15±4	0
ETL	L	17	18	0.46	0.14	17.6	0
ASTRA-ETL	L	21	23	0.26	0.1	6.5	0
experiment	H	2.5	6	0.1-0.2	0.15-0.3	4±1.5	5000
ETL	H	10	12	0.34	0.11	9.6	3700
ASTRA-ETL	H	12	15	0.39	0.09	3.9	2900

Time evolution of the fluctuation amplitudes n_{rms}/n and $e\varphi_{rms}/T$, of the corresponding particle flux Γ (in $10^{20}\ /m^2s$) and of the sheared velocity V (in m/s) through the L-H transition is shown in Fig. 2. The time of the transition is determined by the time of sheared flow generation and is 7 ms. Shot#82830 shows a very slow transition with a duration about 10 ms, which means that the input power is slightly above the threshold, so that the difference between L and H regimes is more qualitative than quantitative: the **E×B** velocity is generated up to 3700 m/s, and turbulent fluxes are suppressed twice, but temperature and density profiles do not change noticeably inside the separatrix. Power threshold is very sensitive to separatrix parameters: starting with the L -mode T_{Se} , T_{Si} and n_S (17) and applying 2.5 MW it is not possible to achieve H-mode, while the same power with the set (18) results in edge transport barrier formation.

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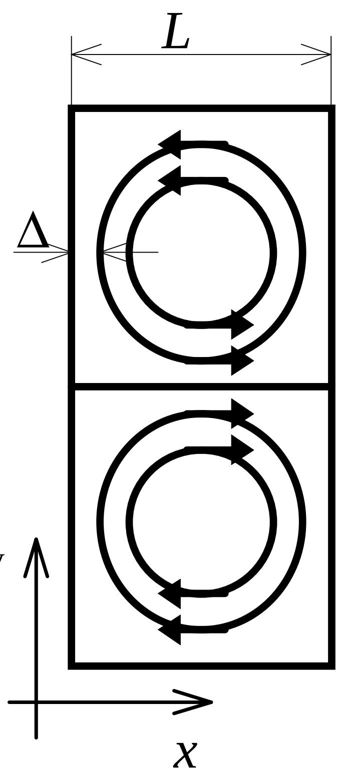

Fig. 1. TL convective cells.

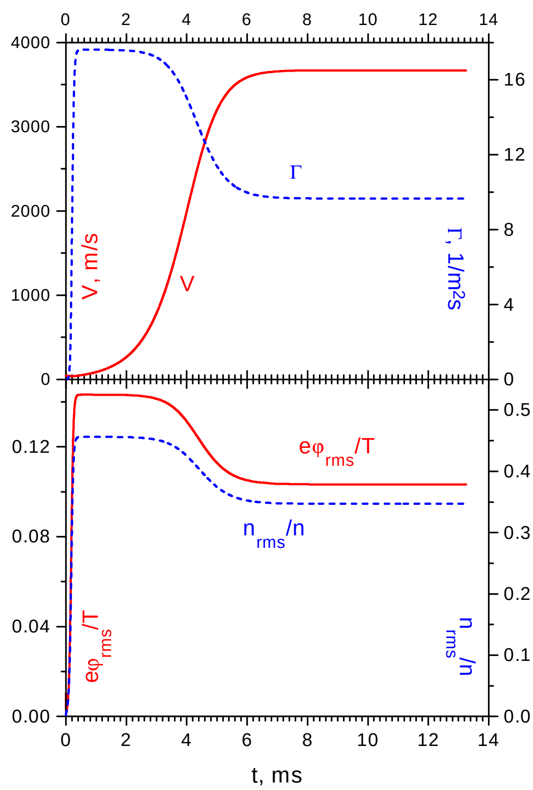

Fig. 2. Time evolution of the L-H transition.