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The role of zonal flows in drift-Alfven turbulence in the edge tokamak plasma.

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Abstract. Turbulence flows were investigated near the resonance point m=nq(x_{res}) at the edge tokamak plasma by means of the numerical simulations of the reduced MHD equations. The role of the zonal flow U_{0y}=c/B∂ϕ_0/∂x and zonal magnetic field B_{0y}= -∂A_0/∂x generated due to nonlinear forces were studied. It was shown that in the case $\beta M_i/m_e>1$ for equal value of the imposed poloidal force the effect of the o turbulence suppression due to shear of velocity U_{0y} is more weaker in comparison with the case $\beta M_i/m_e<1$. This results from cancellation electrostatic and magnetic fluctuations in the Reynolds stress.

Basic equations. We consider tokamak in the slab approximation with magnetic field $\vec{B} = \vec{B}_{eq} + \nabla A \times \vec{e}_z$, $\vec{B}_{eq} = B_0(1-\frac{x}{R_0})[\vec{e}_z + \frac{\varepsilon}{q(r)}\vec{e}_y]$ .Here, x is the radial coordinate and y,z are analogues of the periodic toroidal coordinates. The four-field model of reduced electromagnetic MHD equations [1], in the cold ion limits, are expressed as

$$\frac{DW}{Dt} = -\nabla_{\|}J - g_B(\frac{T_{e0}}{N_0}\frac{\partial n}{\partial y} + \frac{\partial T}{\partial y}) + \mu_{\perp}\cdot\Delta_{\perp}W \quad (1)$$

$$\frac{Dn}{Dt} = -\nabla_{\|}J + g_B\frac{T_{e0}}{N_0}\frac{\partial \phi}{\partial y} + D_{\perp}\cdot\Delta_{\perp}n, \quad (2)$$

$$\frac{3}{2}\frac{DT}{Dt} = -\nabla_{\|}J + g_B\frac{\partial T}{\partial y} + \chi_{\|}\cdot\nabla_{\|}^2 T + \chi_{\perp}\cdot\Delta_{\perp}T, \quad (3)$$

$$\beta\frac{\partial A}{\partial t} = \eta J - \nabla_{\|}(\phi - n - T), \quad (4)$$

Where ϕ is the electrostatic potential, A is the parallel component of the vector potential, $W = \rho^2\cdot\Delta_{\perp}\phi$ the vorticity, $J = \Delta_{\perp}A$ the current density, n,T are the fluctuations electron density and temperature. The total time derivative is $D/Dt = \partial/\partial t + \{\phi,...\}$, $\mu_{\perp}, D_{\perp}, \chi_{\perp}$ are the viscosity, the particle and temperature diffusivity, $\eta = \nu_{ei}/(\omega_{ce}\beta)$ is the resistivity, $\chi_{\|} = 3.16\omega_{ce}T/\nu_{ei}$ is the parallel diffusivity., $g_B = 2x_*/R_0$, $\beta = 4\pi n_* T/B^2$ .The equations (1-4) were nondimensionalized with the help of the transformations

$t \to t/t_*,\ x \to x/x_*,\ \phi \to e\phi/T_*,\ n \to n/n_*,\ T \to T_e/T_*,\ A \to A/A_*,\ b \to b/B_0$

Here $A_* = \beta x_* B_0,\ \rho = \dfrac{\rho_S}{x_*},\ V_* = \sqrt{\dfrac{T_*}{M_i}},\ \rho_S = \dfrac{V_*}{\omega_{ci}},\ \omega_{ci} = \dfrac{eB_0}{M_i c},\ t_* = 1/(\rho^2\omega_{ci}),$

$n_* = 10^{13}\,cm^{-3}$, $T_* = 100eV$, x_*=4cm is the width of the numerical region.

The simulation were performed by Fourier spectral method using modes with the single helicity with k_z/k_y=const. In this case 3D task can be reduced to 2D. For any value f we can write $f(x,y,t) = f_0(x,t) + \sum_{m=1}^{M}[f_{Sm}(x)\sin(mk_y y) + f_{Cm}(x)\cos(mk_y y)]$.

Here the values f_0={N_0,U_0,T_{e0},A_0} are the background or zonal modes (ZM). The ZM flow profiles evolution equations are derived by taking y-averaging of the system (1-4).

$$\frac{\partial N_0}{\partial t} + \frac{\partial \Gamma}{\partial x} = D_0\frac{\partial^2 N_0}{\partial x^2} + S_N \quad , \quad \frac{\partial T_{e0}}{\partial t} + \frac{\partial Q}{\partial x} = \chi_0\frac{\partial^2 T_{e0}}{\partial x^2} + S_T \ ,$$

$$\frac{\partial U_0}{\partial t} + \frac{\partial \Pi}{\partial x} = -\nu_{NEO}\cdot U_0 + S_U \quad , \quad \frac{\partial B_{0y}}{\partial t} - \frac{\partial^2 \Gamma_A}{\partial x^2} = \frac{\partial}{\partial x}\eta\frac{\partial B_{0y}}{\partial x} \quad .$$

Here $\Gamma = \langle n\cdot V_x\rangle + \langle b_x\cdot J\rangle$ and $Q = \langle T\cdot V_x\rangle + \langle b_x\cdot J\rangle + q_\parallel$ are the turbulent particle and temperature fluxes, $\Pi = \rho\cdot\langle V_x V_y\rangle - \dfrac{\beta}{\rho}\langle b_x b_y\rangle$ is the turbulent momentum flux, $\Gamma_A = \beta\left\langle A\dfrac{\partial}{\partial y}(n + T - \phi)\right\rangle$ is the turbulent convective flux of the value A, $q_\parallel = -\chi_\parallel\left[\gamma_\parallel\langle b_x T'_y\rangle + \langle b_x^2\rangle T'_{e0} - \langle b_x\{A,T\}\rangle\right]$. $\nu_{neo} = \dfrac{\nu_{ii}}{\varepsilon^{3/2}(1+\nu_*)(1+\varepsilon^{3/2}\nu_*)}$, $\nu_* = \dfrac{V_{ti}\nu_{ii}}{\varepsilon^{3/2}qR}$. $S_{N,T}$ are the source terms due to atomic and heating processes, S_U is the external y-force. The parallel differential operator $\nabla_\parallel = \vec{b}\cdot\nabla$ was defined as

$$\nabla_\parallel f = \nabla_{\parallel 0} f + B_{0y}\frac{\partial f}{\partial y} + \beta\cdot f_0'\frac{\partial A}{\partial y} - \{A,f\},\quad B_{0y}(x,t) = -\beta\cdot A_0',\ \nabla_{\parallel 0} = \vec{B}_{eqv}\cdot\nabla$$

In the single helicity approximation in the slab geometry we can define operator $\nabla_{\parallel 0}$

$$\nabla_{\parallel 0} f \approx \frac{x_*}{L_S}(x - x_{res})\frac{\partial f}{\partial y},\quad L_S = -\frac{qR_0}{s},\quad s = \frac{rq'}{q}$$

Thus finally we arrive at the following formula $\nabla_\parallel f = \gamma_\parallel\dfrac{\partial f}{\partial y} + \beta\cdot f_0'\dfrac{\partial A}{\partial y} - \{A,f\}$,

where
$$\gamma_\parallel(x,t) = \frac{x_*}{L_S}(x - x_{res}) + B_{0y}(x,t) \qquad (5)$$

The computational domain is 0<x<1.The dissipative coefficients were defined as $\mu_\perp = D_\perp = \chi_\perp = 0.0005$. The magnitudes D_0,χ_0 were chosen to be equal the neoclassical values. The boundary conditions for fluctuations were zero and the background quantities were specified to be N(0)=N_b, T(0)=T_b, U_0(0)=0, B_{0y}(0)=0, N(1)=N_s, T(1)=T_s, U_0(1)=0, B_{0y}(1)=b_{ext}. Our simulations were carried out for the basic set of parameters corresponding to those of the DIII-D tokamak: R=170 cm, a=67 cm, B=2T, M_i=2m_H, q(x_{res})=4, N_b=3.

Simulations results. The basic goal of this work is to study the influence of the ZM: U_0(x,t) and B_{0y}(x,t) on the turbulent transport. In the case of the U_0 our simulations were performed for two different temperature T_b which correspond two regimes: electrostatic with T_b=1,β_M= $\beta M_i/m_e$=0.5 and electromagnetic with T_b=4, β_M=2. In order to vary U_0 we used the nonzero external force S_U(x). This force can be associated with ponderomotive effects due to wave heating. We consider the following model profile S_U(x)

$$S_U = -\frac{dP_{WH}}{dx},\ P_{WH}(x) = P_0 \cdot f(x),\ f(x) = \frac{[t_1 + th(\frac{x - x_{res}}{\Delta x})]}{[t_1 + t_2]},\ t_1 = th(\frac{x}{\Delta x}),\ t_2 = th(\frac{1 - x_{res}}{\Delta x}),$$

with Δx=0.2, x_{res}=0.5

The flux <Γ> is shown in Figure.1 for the different values of parameter P_0 at T_b=1 and T_b=4. Here $<\Gamma> = \frac{1}{T}\int_0^T dt \int_0^1 \Gamma(x,t)dx$ .It is clear that with increasing P_0 the value U_0 increases too. We can see that for low temperature T_b=1 (electrostatic regime) the sheared poloidal flow suppresses the turbulent flux at the edge plasma as it was well known earlier. However at the high temperature T_b=4(electromagnetic regime) for low value P_0 the suppression effect is absent and the flux is decreased only at P_0>0.03. To explain such behavior of the turbulent flux let us consider the Reynolds stress tensor Π=<V_xV_y>-<b_xb_y>. It has two terms, an electrostatic and magnetic components. At low temperature the magnetic fluctuations are very small and the Reynolds stress is large. When the temperature increases the magnetic fluctuations increase too. This cause a near cancellation of these two terms [2,3]. In steady state the value of poloidal velocity is given by

$$U_0 \approx -\frac{1}{\nu_{neo}}\frac{d}{dx}(\Pi + P_{WH}) \qquad (6)$$

It is obvious from (6) that reduction of the Reynolds stress Π due to cancellation at T_b=4 will require the larger magnitude of P_{WH} to get the same value of U_0 for T_b=1.

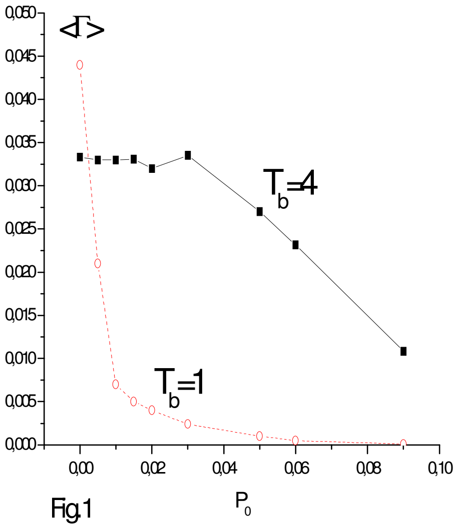

Fig.1

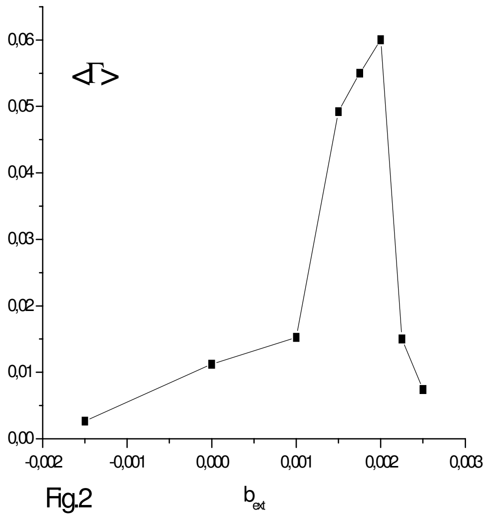

Fig.2

Now we describe the impact of the ZM B_{0y} on the turbulent transport. We suppose existing of the static magnetic field at the edge tokamak plasma. It can be induced, for example, by the external current. This field is introduced through a nonzero boundary condition $B_{0y}(x=1)=b_{ext}$. In calculations we vary b_{ext} from $b_{ext}=-0.002$ to $b_{ext}=0.004$. The dependence of the flux $\langle\Gamma\rangle$ on the value of b_{ext} is plotted in Figure.2 for $T_b=3$.In order to understand this plot we have to return to equation (5). We can see that the value of $\gamma_{\|}$ consists of the two terms. The first is the well known magnetic shear term which produces suppression of the Alfven-drift instability in linear approach and therefore would act as suppression factor in the nonlinear case of Alfven-drift turbulence. Evidently, effect of the second term is connected with B_{0y} on the value $\gamma_{\|}$ dependents on the sign of B_{0y}. Note as the magnitude of B_{0y} oscillates we bear in mind the time averaging value. When $B_{0y}>>\Delta x/L_S$ or $B_{0y}<<\Delta x/L_S$ the strong suppression of the turbulent fluxes takes place. When $B_{0y}\sim\Delta x/L_S$, $\gamma_{\|}<<1$ the effect of the magnetic shear stabilization disappears resulting in rise of turbulent flux .

References.

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