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Evolution of turbulent transport during the formation of internal transport barrier in tokamak

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In this work the stabilizing effect of the ExB rotation shear on the properties of the RBM and associated turbulent transport is studied using 3D numerical code [1]. The ExB rotation shear stabilization of the turbulent transport driven by the RBM and current-diffusive ballooning modes (CDBM) [2] are compared. The specific issues addressed here are the threshold in the ExB shear stabilization of the RBM and the effect of the toroidal magnetic field on the RBM and associated transport. Finally, the rotation shear stabilization of the ITG turbulence [3] and RBM is compared and the application of our results to the experimental scenarios with an internal transport barrier (ITB) is discussed.

1. Model for RBM

The model for the RBM consists of a pressure and vorticity equation where the parallel electric current has been estimated using the Ohm's law. Only electrostatic fluctuations have been taken into account in our simulations. The equilibrium pressure profile has been calculated using the balance between a prescribed central source and turbulent and neoclassical fluxes which allows a self-consistent estimation of the equilibrium pressure and turbulence (so called "flux-driven turbulence" approach). A standard ballooning transformation has been employed and the modes with the toroidal number up to n=24 have been included in the simulations. The simulations have been performed for the magnetic configuration with monotonic q-profile for the plasma layer located between the q=2 and q=3 surfaces. A more detailed description of the model is given in Ref. 1.

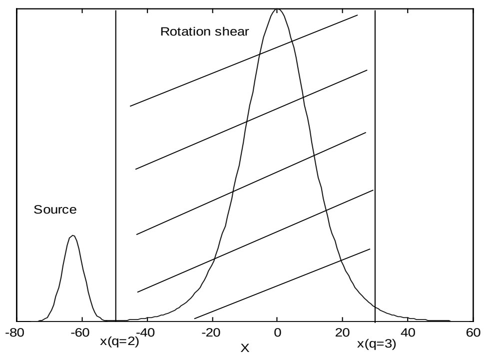
The stabilizing effect of the **E**x**B** rotation shear on the RBM has been studied by varying an externally imposed **E**x**B** flow in the pressure equation. The normalized shearing parameter, $\alpha(r) = 0.5(1/c_s)(L_pR)^{1/2}\partial_r E_r/B_t$ (here c_s is the ion sound velocity, L_p is the pressure gradient length, R is the major radius, E_r is the radial electric field and B_t is the toroidal magnetic field) has a Gaussian radial profile and its maximum, α_{max}, has been varied from 0 (shearless case) to 0.9 (Fig.1). In these simulations we do not take into account a self-generated **E**x**B** rotation shear. Previous simulations of the turbulent transport driven by the RBM showed that the stabilizing effect of the self-generated ExB rotation shear on the turbulent flux is not sufficient to generate a transport barrier [4]. It has been found that the self-generated ExB rotation shear produces the "smoothing" of the radial profile of the turbulent flux by reducing its value near the rational surfaces where the concentration of the modes is larger.

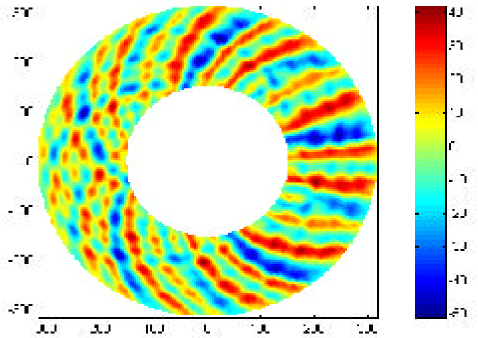
2. ExB shear stabilization of the turbulent flux driven by RBM

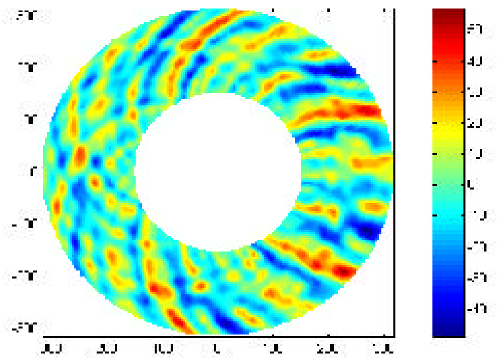
The effect of the ExB rotation shear on the radial structure of the RBM is illustrated in Fig. 2 where the contour plots of the electrostatic potential for the shearless case and for the case with intermediate (α_{max} = 0.3) and large (α_{max} = 0.9) rotation shear are presented. The destruction of the large scale radial structure of the modes due to large ExB rotation shear is clearly shown in these simulations. Interestingly, a small destabilizing effect of the rotation shear on the amplitude of the potential fluctuations has been found at a low ExB rotation shear values (Fig. 2 left bottom) while the amplitude reduces at a large ExB shear. Similar destabilizing effect of the low rotation shear has been found previously for the ITG turbulence. It has been shown that the ITG turbulence displays an increase of maximum growth rate with a small shear [3]. The flux surface averaged equilibrium pressure profiles for the L-mode-like plasma (α=0) and a plasma with a fully stabilized RBM-driven transport (α=0.9) clearly show the formation of the transport barrier in the plasma region with large rotation shear (Fig. 3). To illustrate the effect of the toroidal magnetic field on the structure of the RBM and associated transport the simulations of the RBM have been performed at a lower value of magnetic field ($B_t \rightarrow 0.5B_t$) while keeping other parameters constant. It has been found that the RBM-driven turbulent flux is weakly sensitive to the value of the magnetic field whereas the amplitude of the potential fluctuations first strongly increases with the increase of the rotation shear and then relaxes at lower B_t -values.

The effect of these modifications of the RBM properties by the externally imposed ExB rotation shear on the turbulent transport is shown in Fig. 4 where the local turbulent diffusivity, χ, estimated in the gradient region (see Fig. 1) is plotted as a function of the local shearing parameter α for $0 \leq \alpha \leq 0.9$. For a further application, the results of the numerical simulations have been approximated with the fitting function. As one can see from Fig. 4 the best fit of the simulation results has been obtained with the algebraic function, $F(\alpha) = 1/(1+30\alpha^2)$ (Fig. 4, solid curve) which gives smoother reduction of the heat diffusivity with the increase of the shear than the exponential fit (dashed curve).

The stabilizing effect of the ExB rotation shear on the turbulent diffusivity produced by the pressure gradient driven ballooning modes in resistive approximation has been compared with the ExB rotation shear correction for the heat diffusivity driven by the CDBM [2]. In spite of the similar basic physics used in these approaches some distinctions must be mentioned here. Thus, in our approach the parallel current is estimated from the Ohm's law using the classical conductivity whereas the approach of Ref. 2 includes electron viscosity as a dominant term. These assumptions specify the region of application of the different approaches - the RBM are dominant at the plasma edge where the temperature is low whereas the CDBM may produce the turbulent transport well inside the last closed magnetic surface. The RBM and CDBM have different shearing parameters since different physical mechanisms are involved which makes difficult the explicit comparison of the shear stabilization of these types of turbulence. For some comparison, the ExB rotation shear correction in turbulent diffusivity driven by the CDBM is plotted as a function of its shearing parameter, $\alpha_{CDBM} = (\tau_{Ap}/s)\partial_r E_r/B_t$ (here all notations are from Ref. 2) in Fig. 5. As an example, we estimate the α_{CDBM} -value with the experimental parameters of a typical JET optimized shear scenario (shot 40847) in the plasma region r/a>0.4 during the transition from the L-mode to the ITB phase and H-mode. The radial electric field is calculated from the balance of experimental toroidal and diamagnetic rotation and neoclassical poloidal rotation. As one can see from this figure the heat diffusivity driven by the CDBM is strongly suppressed during the ITB formation. The comparison with the RBM shows that the rotation shear suppression of turbulent transport driven by the CDBM and RBM are similar for $\alpha = 0.63\alpha_{CDBM}$ whereas it is much more complicated to stabilize the RBM at lower α/α_{CDBM}-ratios (black curve in Fig. 5) which are more relevant to the experimental conditions. This may have consequences to the radial extension of the transport barrier produced due to the stabilization of the CDBM since a larger rotation shear value will be required for the extension of this transport barrier towards the plasma edge where the RBM-driven turbulent flux is the dominant one.







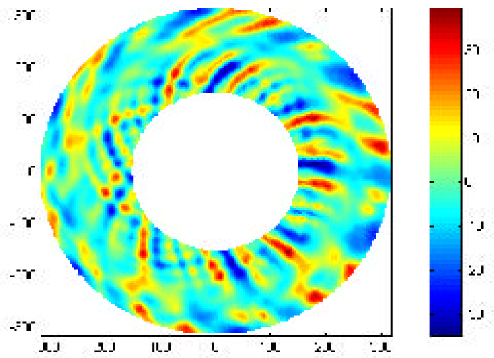


Fig. 1(left, top). Simulation parameters: pressure source and imposed ExB rotation shear. Vertical lines show the simulation domain used for the estimation of turbulent diffusivity

Fig. 2 (right top, left and right bottom): Contour plots for electrostatic potential in the poloidal plane for the shearless case (α=0, top), α=0.3 (left bottom) and α=0.9 (right bottom).

3. Discussion

The effect of an externally imposed ExB rotation shear on the structure and properties of the RBM and associated turbulent transport has been studied using a 3D numerical code. It has been shown that strong ExB rotation shear reduces the fluctuation amplitude and affects the radial structure of the modes by decreasing its radial extension. This modifies the plasma transport properties providing a strong reduction of turbulent heat diffusivity.

The characteristics of the turbulent heat diffusivity (a slow reduction of χ-value with an increase of the ExB rotation shear and the absence of the threshold in the ExB shear stabilization of the turbulent flux) obtained in this paper for the RBM and similar results for the ITG turbulence [3] and CDBM [2] are not the same as a characteristics of the empirical shear corrections validated in the modelling of the temperature and density evolution in experimental advanced scenarios. The multi-machine modelling of thermal ion transport in experimental advanced scenarios with an ITB shows that the sharp exponential dependence of the heat diffusivity on the ExB rotation shear and the threshold in the ExB rotation shear stabilization are required to reproduce the experimental temperature and density evolution [5]. The need in the threshold in the ExB rotation shear stabilization is clearly demonstrated by the transport modelling of the L-mode plasmas with shear-independent transport coefficients where the rotation shear increases with the increase of the additional heating power (but it still remains below some threshold value) while the confinement time decreases. The tendency to obtain a shear-independent heat diffusivity at low shear values has been illustrated in the gradient-driven ITG turbulence simulations where the χ–value may not change within some range of shear values due to the balance between increasing rotation shear and growth rate. However the flux-driven ITG turbulence simulations similar to ones performed here for the RBM are required to quantify the rotation shear effects on the turbulent transport.

References: 1. Beyer P., et al., Phys. Plasmas, **5** (1998), 4271 and PRL, submitted; 2. Itoh S.-I., et al., Phys. Rev. Lett., **72** (1994), 1200; 3. Waltz R. E., Dewar R. L., Garbet X., Phys. Plasmas, **5** (1998), 1784; 4. Beyer P., private communication; 5. Voitsekhovitch I., et al., Phys. Plasmas **6** (1999), 4229; 26th EPS Conf. on Contr. Fus. and Pl. Phys., vol. **23J** (1999), 957

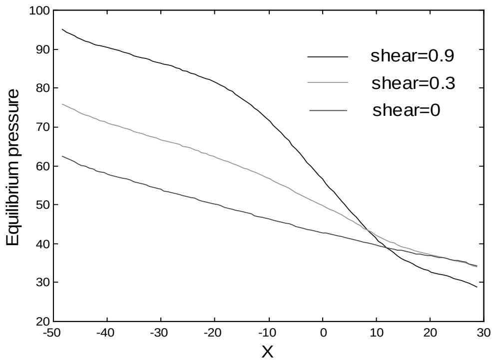


Fig. 3. Flux surface averaged pressure profiles

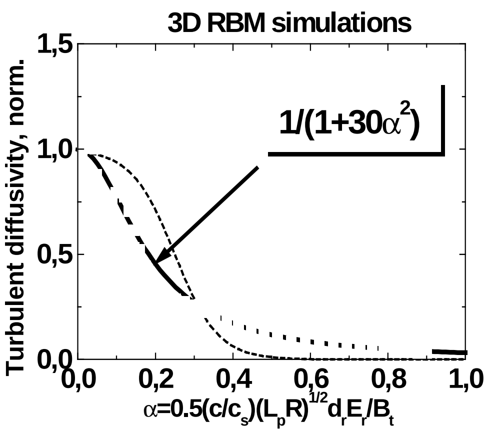


Fig. 4. Ratio $\chi(\alpha)/\chi(\alpha=0)$ as a function of the ExB rotation shear. Symbols shows the results of 3D simulations.

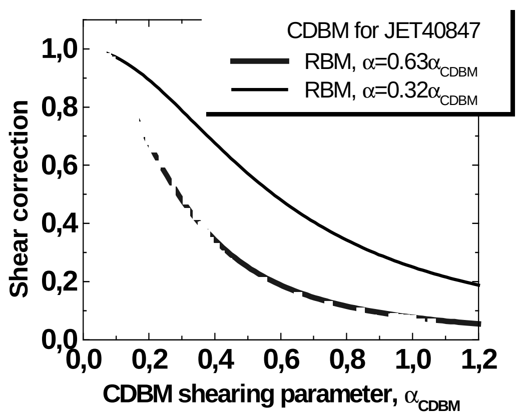


Fig. 5. Comparison of the rotation shear stabilization of the turbulent transport driven by the RBM and CDBM