ITB formation in simulations of nonlinear turbulent convection in tokamak core plasmas

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Internal transport barrier (ITB) is one of the challenging problems for improved plasma confinement in tokamaks. At the present time a number of theories were proposed to explain ITB. These theories assume some mechanism for turbulent fluctuations decorrelation in the vicinity of ITB zone, which leads to the reduction of turbulent heat and particle fluxes. Most of these theories associate fluctuations suppression with strong $E \times B$ shear [1, 2]. At the same time, the analysis of the experimental results obtained in different tokamaks (MAST, RTP, TEXTOR, DIII-D) [3, 4, 5], cause some doubts that the shear of the plasma rotation is the main reason of ITB formation in tokamaks. Another concept of ITB formation is associated with magnetic shear and magnetic field structure [6]. It is based on following assumptions: all turbulent fluctuations can be represented as harmonics of poloidal θ and toroidal φ angles. The harmonic of fluctuations with toroidal number n and poloidal number m is localized in the vicinity of a rational magnetic surface(RMS), where safety factor q=m/n with corresponding numbers m and n.Due to partial overlapping and toroidal and/or nonlinear coupling of such (m,n)-harmonics of fluctuations in areas with a sufficiently dense distribution of RMS, the harmonics with succeeding m-numbers can form linked radially extended chains. Such radially extended chains of linked harmonics with limited n-numbers can form the dominant turbulent-convective cells those give the main contribution to the resulting anomalous heat and particle fluxes. As it is seen from Fig.1, there are enhanced intervals ("gaps") between RMS q=m/n with the limited n-numbers and the major RMS with integer and half-integer values of q. The last feature is able to break the link between convective cells. As a result, the anomalous cross-field heat and particle transport has to be locally decreased.

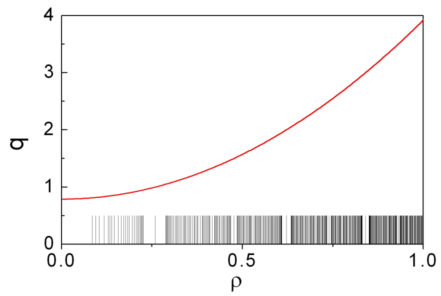

Figure 1: Profile of safety factor $q(\rho)$ and the radial distribution of the RMS with toroidal numbers $n \leq 20$

Our simulations are based on a relatively simple MHD-like model of low frequency(LF) electrostatic plasma convection [7]. The LF turbulent convection in our simulations is described by a set of coupled nonlinear equations for the toroidal harmonics of dynamic vorticity w_n, the electric potential fluctuations ϕ_n (which define the fluctuations of turbulent velocity), the fluctuations of entropy function $S_n = p_n U^2$, and the fluctuations of number of particles $D_n = n_n U$ in the specific volume U of the magnetic flux tube. Harmonics are marked with toroidal numbers $0 < n < n_{max}$. In order to take into account the influence of magnetic shear we introduce extra conditions into our model. These conditions emulate the interruption of harmonics with moderate toroidal numbers $n < n_b < n_{max}$ at some points inside the gap near the major rational magnetic surface. The correctness of these conditions can be established with the following logic. Let's assume, that a second order partial differential equation(PDE) is satisfied in the vicinity of some point, then at this point the PDE is equivalent to two conditions, i.e. continuity of function and continuity of this function first derivative. Our extra conditions for pressure and density fluctuations replaces the latter and leads to break in the first order function radial derivative at this point. However, the subset of equations for fluctuations of dynamic vorticity and potential with corresponding toroidal number n is strongly coupled. Also we need to keep the continuity of dynamic vorticity and first radial derivative of potential in order to avoid non-physical energy sinks and sources. We can consider this subset as a fourth order PDE, and replace the continuity of potential third radial derivative (i.e. first radial derivative of vorticity) with extra condition for potential fluctuation harmonic following the same logic as for the second order PDE. So we add to our model extra conditions for potential,pressure and density fluctuations with toroidal numbers $n < n_b$, which nullifies these harmonics at some points near major RMS. Typical behavior of vorticity and potential harmonics profiles with extra condition is demonstrated on Fig.2

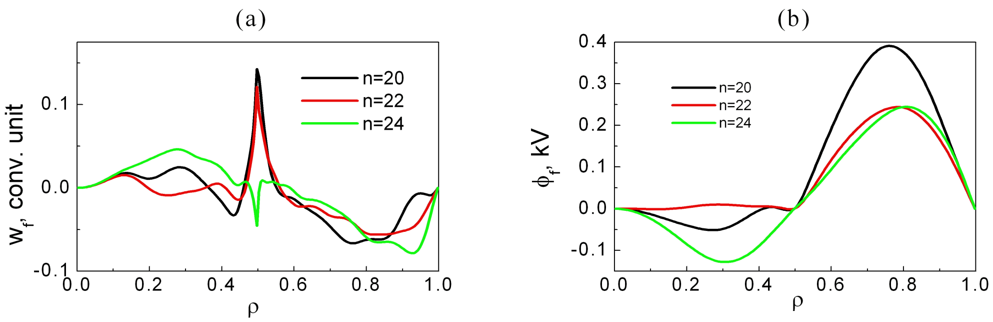

Figure 2: Harmonics of fluctuations($n < n_b$) for (a) dynamic vorticity, (b) potential, with extra condition at q=3/2

In this paper we present results of simulations for regime with 1.1MW of central electron cyclotron resonance heating(ECRH). Major plasma radius is 1.5m, minor plasma radius is 0.3m. The total number of toroidal harmonics for these simulations was $n_{max} = 84$. Extra conditions are added at $q = 3/2$ surface. S_0 profiles for various potential differences are presented

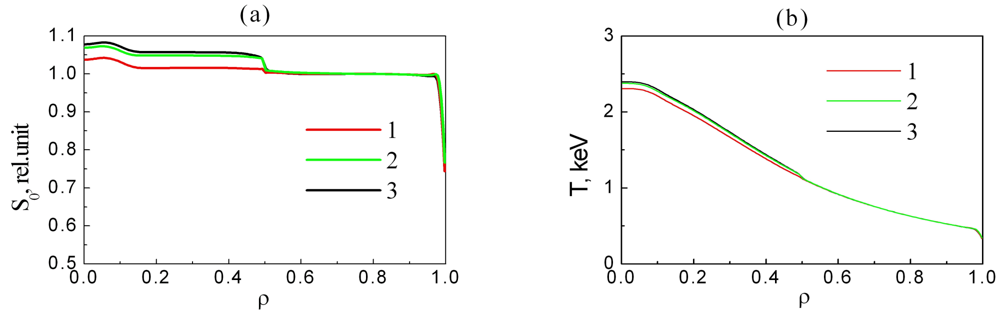

Figure 3: Entropy function (a) and temperature (b) profiles for various potential differences: 1-0 kV, 2 - 0.5 kV, 3 - 2.0 kV

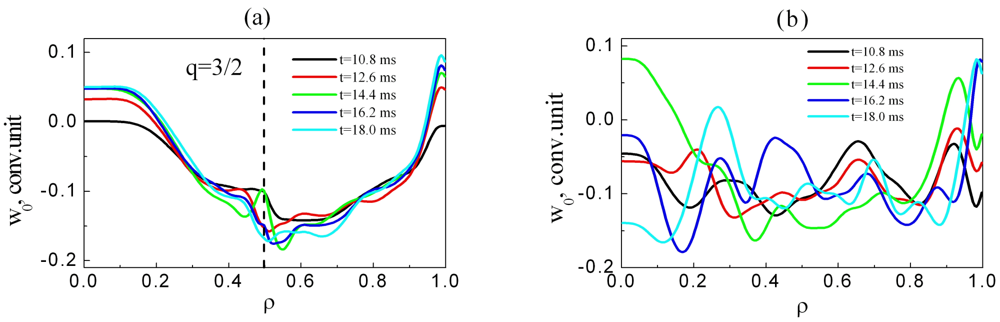

Figure 4: Profiles of mean vorticity at different time moments. (a) extra condition at q=3/2, (b) without extra conditions

at Fig.3(a). These profiles have steeper gradient, in comparison to canonical pressure profile which corresponds to $S_0 = const$, at the point where extra condition is added. Corresponding temperature profiles are presented at Fig.3(b). w_0 profiles for $n_b = 60$ at different time moments are shown at Fig.4(a). These profiles show the formation of w_0 extremum near $q = 3/2$ which corresponds to the shear of toroidal rotation. It should be noted that no such extremum is formed without extra condition Fig.4(b). So in our model ExB shear is not a reason, but consequence, of ITB formation.

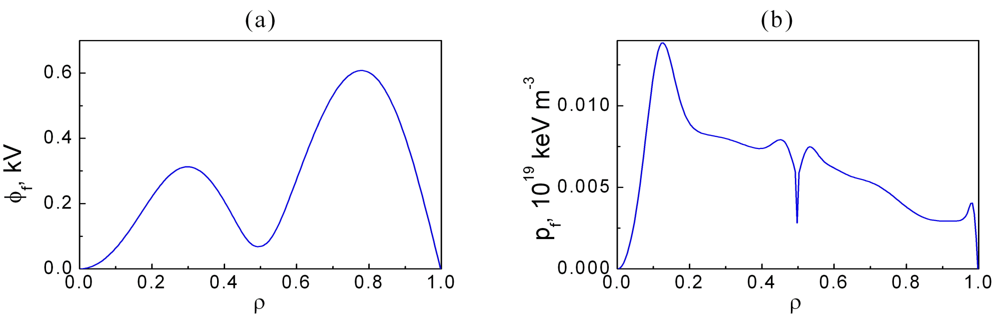

Figure 5: Fluctuation levels of potential (a) and plasma pressure(b)

The amplitudes of fluctuations of p_f and ϕ_f are reduced near the extra condition. Very important that the level of ϕ_f even at the ECRH stage is about 100-200V in the presence of the additional boundary conditions. It is comparable with the experimental level and is significantly reduced (approximately 10 times) in comparison with the ϕ_f level in our previous simulations without extra conditions. The level of pressure fluctuations is also reduced.

Summary

Additional conditions were added at the point of major RMS to emulate effects of magnetic shear. These conditions lead to formation of steeper pressure gradient at the point of this RMS. Turbulent fluctuations level is significantly reduced in comparison with simulations without extra conditions. Enhanced $E \times B$ shear is formed near the point with extra conditions.

References

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