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Role of Flow Shear in Enhanced Core Confinement Regimes

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Abstract

The importance of the $\mathbf{E} \times \mathbf{B}$ flow shear in various enhanced confinement regimes is discussed in terms of the turbulence suppression criterion in toroidal geometry. This criterion is then further generalized to include the poloidal angle dependence of the equilibrium electrostatic potential. The implication of the recently observed in-out asymmetry in the fluctuation behavior in DIII-D VH-mode is discussed.

I. Introduction

It is well known that the $\mathbf{E} \times \mathbf{B}$ flow shear plays a crucial role in the L to H transition of many tokamak plasmas[1–4]. In this paper, the importance of $\mathbf{E} \times \mathbf{B}$ flow shear in various enhanced core confinement regimes is discussed. Our recent nonlinear theory of flow shear induced fluctuation suppression in an arbitrary shape finite aspect ratio tokamak plasma[5] indicates that the radial shear of $E_r^{(0)}/RB_\theta$ is the quantity of interest. This result has compared well with magnetic braking experiment on VH-mode in DIII-D [6]. While this criterion can be applied universally to various enhanced confinement regimes in tokamaks[1, 2, 6], their dominant contributors to this term vary. A possible origin of this term can be plasma rotation due to unbalanced neutral beam injection (such as in the DIII-D VH-mode) or ion Bernstein waves (PBX-M CH-mode[7]), as well as peaked ion pressure profiles (TFTR Supershot[8]). Furthermore, from the explicit dependence on B_θ, we can gain new insight into the confinement improvement in reversed shear configurations[9, 10].

In Sec. III, our previous fluctuation suppression criterion in toroidal geometry[5, 11] is further generalized to include the poloidal angle dependent part of the equilibrium electrostatic potential which can be produced by a strong toroidal rotation of low density plasmas[12, 13]. Finally, a recently observed in-out asymmetry in the fluctuation behavior in DIII-D VH-mode plasma[14] is discussed in Sec. IV.

II. Role of E×B Flow Shear in Enhanced Core Confinement Regimes

In our previous work[5], it has been shown that the fluctuation suppression occurs when the decorrelation rate of the ambient turbulence $\Delta\omega_T$ is exceeded by the following shearing rate ω_s in toroidal geometry, $\omega_s \equiv (\frac{\Delta\psi_0}{\Delta\phi})|\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi)| = (\frac{\Delta\psi_0}{\Delta\phi})|\frac{\partial}{\partial\psi}(\frac{E_r^{(0)}}{RB_\theta})|$. Here, $\Delta r_0 \equiv \Delta\psi_0/RB_\theta$ and $R\Delta\phi$ are the correlation lengths in the radial and toroidal directions respectively. The radial force balance equation relates $E_r^{(0)}$ to plasma rotation velocity and the pressure gradient, $E_r^{(0)} = u_\phi B_\theta - u_\theta B_\phi + \frac{1}{n_i e_i}\frac{\partial}{\partial r}P_i$. Straightforward manipulation of this relation leads to an expression which exhibits various contributors to the quantity of interest, the radial shear of $E_r^{(0)}/RB_\theta$;

$$\frac{\partial}{\partial\psi}\left(\frac{E_r^{(0)}}{RB_\theta}\right) = \frac{\partial}{\partial\psi}\left(\frac{u_\phi}{R}\right) - \frac{\partial}{\partial\psi}\left(\frac{u_\theta B_\phi}{RB_\theta}\right) + \frac{1}{e_i}\frac{\partial}{\partial\psi}\frac{1}{n_i}\frac{\partial}{\partial\psi}\left(n_i T_i\right). \tag{1}$$

In the following examples, there is evidence that $\mathbf{E}\times\mathbf{B}$ flow shear plays a crucial role in the confinement improvement. We indicate the relative importance of each term on the right hand side for various enhanced confinement regimes.

(i) H-mode in DIII-D; In the plasma edge across the L to H transition, the ion poloidal flow and the pressure gradient terms are both important. While the initial change in E_r is believed to be due to a change in u_θ, most of the fluctuation suppression occurs in the later phase in which the pressure gradient term becomes important[2, 6].

(ii) VH-mode in DIII-D; Due to broad E_r shear layer, the toroidal theory specific geometric factors in Eq.(1) are quite important. Magnetic braking experiments on VH mode in DIII-D indeed show that there is a clear reduction in the thermal diffusivity in the same region where the shear in E_r/RB_θ has changed. Most contribution to $\frac{\partial}{\partial\psi}(\frac{E_r^{(0)}}{RB_\theta})$ comes from the toroidal flow contribution (the first term on the RHS)[6].

(iii) CH-mode in PBX-M; Location of the internal transport barrier is consistent with the ion Bernstein wave induced ponderomotive force driven poloidal shear flow model[7, 15].

(iv) Supershot in TFTR; Reduction of radial correlation length with increasing toroidal velocity has been observed[16] in qualitative agreement with the prediction of the two point nonlinear theory in toroidal geometry[5, 11]. The region of sharp gradient of u_ϕ approximately corresponds to that of T_i [17]. It is interesting to observe that for co-NBI, the toroidal flow term and the last term on the RHS add, making the fluctuation suppression easier. The last term can be written as a sum of the following two terms which are both negative for the typical peaked profiles at tokamak plasma core,

$$-\frac{1}{n_i^2}(\frac{\partial n_i}{\partial \psi})\frac{\partial}{\partial \psi}(n_i T_i) + \frac{1}{n_i}\frac{\partial^2}{\partial \psi^2}(n_i T_i).$$

(v) Enhanced Reversed Shear Modes in TFTR and DIII-D; Although more quantitative data analyses are needed to confirm the importance of $\mathbf{E} \times \mathbf{B}$ flow shear, aforementioned observation regarding the signs of toroidal flow term and the last term also applies to this case. Furthermore, the B_θ dependence contained in the definition of the poloidal flux ($\frac{\partial}{\partial \psi} \equiv \frac{1}{RB_\theta}\frac{\partial}{\partial r}$) tends to enhance the relative importance of the pressure and density gradient terms (the last term on the RHS of Eq.(1)) in comparison to the flow terms in the reversed shear region. Therefore, it is essential that this expression in toroidal geometry must be used in comparison to the experimental data to properly address the physics origin of the enhanced confinement in reversed shear mode[9, 10].

III. Effects of Poloidal Angle Dependent Electrostatic Potential

In our previous works[1, 5], $\Phi^{(0)}$ has been assumed to be a flux function. This simplifying assumption needs to be improved when there is strong toroidal plasma rotation. In this case, $\Phi^{(0)}$ depends on the poloidal angle θ also and the two point nonlinear analysis becomes more involved. A crucial modification comes through the introduction of θ-dependence of $E_r^{(0)}$ as well as $E_\theta^{(0)}$. Now, $V_E^{(0)}$ has a radial component as well as the usual (non radial) perpendicular component. The radial and poloidal variations of each component must be included in the two point nonlinear analysis. The two-point correlation evolution equation is then derived following the standard procedure,

$$\left\{\frac{\partial}{\partial t}+\left(\psi_-\Omega_{\psi\psi}+\eta_-\Omega_{\theta\psi}\right)\frac{\partial}{\partial\phi_-}-\left(\psi_-\Omega_{\psi\theta}+\eta_-\Omega_{\theta\theta}\right)\frac{\partial}{\partial\psi_-}-D_-^{\rm eff}\frac{\partial^2}{\partial\phi_-^2}\right\}<\delta H(1)\delta H(2)>=S_2. \tag{2}$$

Here, the radial shear and poloidal variation of the angular rotation frequency in perpendicular direction are given by $\Omega_{\psi\psi}\equiv-\frac{\partial^2}{\partial\psi^2}\Phi^{(0)}(\psi,\theta)$ and $\Omega_{\theta\psi}\equiv-\frac{\partial^2}{\partial\theta\partial\psi}\Phi^{(0)}(\psi,\theta)$. The radial shear and poloidal variation of the radial $\mathbf{E}\times\mathbf{B}$ velocity are given by $\Omega_{\psi\theta}\equiv\frac{\partial}{\partial\psi}(\frac{1}{\nu}\frac{\partial}{\partial\theta}\Phi^{(0)}(\psi,\theta))$ and $\Omega_{\theta\theta}\equiv\frac{\partial}{\partial\theta}(\frac{1}{\nu}\frac{\partial}{\partial\theta}\Phi^{(0)}(\psi,\theta))$. Here, ν is the local magnetic field pitch. Other notations are standard and have been defined in Hahm and Burrell[5]. The results of two point nonlinear analysis indicate that fluctuation suppression occurs when the following inequality involving the decorrelation rate of the ambient turbulence $\Delta\omega_T$ and the shearing rates, ω_s and $\Omega_{\psi\theta}$ is satisfied;

$$\omega_s^2\equiv\left(\frac{\Delta\psi_0}{\Delta\phi}\right)^2\left|\frac{\partial^2}{\partial\psi^2}\Phi^{(0)}(\psi,\theta)\right|^2>\Delta\omega_T(\Delta\omega_T+\Omega_{\psi\theta}). \tag{3}$$

We observe that $\Omega_{\psi\theta}$ vanishes at the mid-plane where the fluctuations are typically measured. Therefore, our previous criterion for the fluctuation suppression[5] can still be applied there. $\Omega_{\theta\psi}$ and $\Omega_{\theta\theta}$ do not affect the fluctuation level directly, although they distort the shape of the eddies.

IV. In-Out Asymmetry in Fluctuation Suppression

The investigation of in-out asymmetries in fluctuation suppression not only imposes a stringent test on the hypothesis of flow shear induced suppression of turbulence, but also provides useful information on the nature of ambient turbulence. Recent results from the heterodyne FIR scattering measurements of density fluctuations in DIII-D VH-modes with magnetic braking[14] have indicated the following interesting features.

(i)The spectral intensity which originates from the strongly rotating VH-mode plasma core is feeble. This suggests that the core turbulence is suppressed due to the $\mathbf{E}\times\mathbf{B}$ flow shear.

(ii) After the magnetic braking is applied, lowering the plasma rotation, the broadband turbulence associated with the core returns. Interestingly, the spectral range of turbulence which initially returns is associated with the portion of the core on the high field side (inside). To be compatible with this observation, the flow shear induced turbulence suppression criterion presented in Eq.(3) must have been violated at the inside first.

(iii) After the plasma slows down considerably, the intensity which originates from the low field side (outside) is higher than that from inside. This implies a ballooning-like character of the ambient turbulence with higher amplitude at the outside.

Since the ambient turbulence is stronger at the outside as observed in phase (iii), the shearing rate must be significantly higher at the outside to explain the feature in phase (ii). As discussed in Ref. 5, since density fluctuation measurements via microwave scattering are performed for a number of specific values of k_θ which are determined by the scattering geometry, it is more useful to write ω_s in terms of $\Delta\theta = \Delta\phi/\nu$ and Δr_0; $\omega_s = (\frac{RB_\theta \Delta r_0}{\nu \Delta\theta})|\frac{\partial^2}{\partial\psi^2}\Phi^{(0)}(\psi)|$. Then, for fixed $\Delta\theta$, ω_s varies like $RB_\theta/\nu \simeq (RB_\theta)^2/rB_\phi \propto R^3$, and the shearing rate is significantly higher at the large major radius side. We recall that the origin of the major radius dependence is flux expansion ($\Delta\psi = RB_\theta\Delta r$) and the variation of the local magnetic pitch ν. Another possible origin of the poloidal angle dependence in the shearing rate is strong plasma toroidal rotation[12, 13] as discussed in Sec.III. In this case,

$$\Omega_{\psi\psi} \simeq -\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi) + \frac{M_i R_0 cos\theta}{e_i}\frac{\partial^2}{\partial\psi^2}\left[\frac{T_e}{T_i + T_e} r\omega(\psi)^2\right], \tag{4}$$

where $\omega_s \equiv (\frac{\Delta\psi_0}{\Delta\phi})|\Omega_{\psi\psi}|$, and $\omega(\psi)$ is the angular frequency of the plasma toroidal rotation.

In conclusion, $\mathbf{E} \times \mathbf{B}$ flow shear induced suppression of turbulence still remains the best hypothesis for the confinement improvement even after the emergence of various core enhanced confinement regimes and more sophisticated fluctuation measurements.

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