A RECONSIDERATION OF INTERNAL TRANSPORT BARRIER MODELS IN REVERSE SHEAR PLASMAS

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1. Introduction

To explain the physical origin of the internal transport barrier(ITB), observed in reverse shear plasmas, several models have been proposed. Such models may be divided into two groups; One is the $\mathbf{E} \times \mathbf{B}$ shear flow model[1], where the main ITB trigger is the stabilizing $\mathbf{E} \times \mathbf{B}$ shear flow, similar to the well-known L-H transition case in edge. This model is based on the neoclassical theory that a radial electric field E_r can occur from the ion pressure gradient $p_i^{'}$ through the neoclassical diffusion (or magnetic pumping) process in core plasma. The role of reverse shear in this model is secondary, just helping the build-up of the pressure gradient to the threshold value. The other model is the weak magnetic shear model [2-3], where the main trigger is the stabilization of the long wavelength toroidal drift modes or the enhancement of the stabilizing shear flow effect by the weak magnetic shear. This model is based on the theoretical and numerical observations of the local gap or discontinuity generation in the global toroidal ITG mode structure around the weak magnetic shear region, and the enhancement of such a gap or discontinuity degree with increasing flow shear.

In this work, we present a reconsideration of these two models. We first present a brief summary of the $\mathbf{E} \times \mathbf{B}$ shear flow model, its comparison with some important experimental observations, and a discussion of its weak points. We then do the similar work for the weak shear model, but with a newly developed scenario of the ITB formation. We first summarize some important experimental observations in the reverse shear plasmas [4] for the comparison with the models; (a) A threshold input power is necessary to get the ITB. (b) The ITB region is typically located inside of $q_{\min}$ position, expanding with it. The location of ITB foot is near $q_{\min}$, even though there seems to be no clear matching between them. (c) Back transition from ERS to RS is observed in TFTR with a different direction of toroidal flow velocity. The degradation starts from the ITB foot and propagates inward [5]. (d) A strong transient v_θ with $E_r < 0$ is observed near $q_{\min}$, just before the ITB formation in TFTR [6].

2. $\mathbf{E}\times\mathbf{B}$ shear flow model

Basic scenario: As mentioned earlier, a basic element of this model is the generation of E_r from $p_i^{'}$ through the neoclassical diffusion process. The resulting $\mathbf{E}\times\mathbf{B}$ flow shear stabilizes completely the drift-type fluctuation when

$$\omega_{E\times B} > \gamma_{\max}, \tag{1}$$

through the nonlinear decorrelation or linear breaking of the global mode structure, where $\omega_{E\times B}$ is the $\mathbf{E}\times\mathbf{B}$ shearing rate and $\gamma_{\max}$ is the maximum linear growth rate of the trapped electron and/or ITG mode. Here, from the different $p_i^{'}$ dependence of $\omega_{E\times B}$ and $\gamma_{\max}$, like

$$\omega_{E\times B} \propto E_r \propto p_i^{'}, \qquad \gamma_{\max} \propto (p_i^{'})^{1/2} \ \text{(approximately)}, \tag{2}$$

a threshold pressure gradient exists above which $\omega_{E\times B} \geq \gamma_{\max}$ so the mode becomes secondly stable. Once the threshold condition is satisfied, the pressure gradient increases continuously and the ITB region propagate inside and outside, until when the heat transport is balanced by neoclassical transport or the plasma is disrupted by some MHD instabilities.

Explanation of experimental observations: (a) Power threshold is required for the pressure gradient to arrive at the threshold value. (b) The stabilizing effect of the negative shear itself and Shafranov shift increased in the negative shear region on the trapped electron or toroidal ITG mode makes it easy for the plasma to reach the condition (1). (c) The E_r from V_ϕ can increase or decrease the E_r from the pressure gradient, depending on its sign. The degradation starts from the ITB foot since here the condition (1) is marginally satisfied. (d) There seems to be no clear explanation yet about this.

Question and check points: (i) Can the generation of E_r from the neoclassical diffusion be still effective under the anomalous diffusion situation? There can be the other non-ambipolar diffusion process, for example, due to the stochastic electron diffusion or the ambipolarity breakdown by the finite ion Larmar radius (FLR) effect in the short wavelength fluctuations driven transport (see Sec. 3). These fluctuation-induced E_r has the opposite sign to that induced neoclassically from the pressure gradient, so can cancel out it. (ii) It is not clear why the ITB was not observed in the plasma regimes such as the hot ion or supershot, where the ion pressure gradient was large due to the large η_c. (iii) In the core plasma region where ITB is typically formed, the ion temperature takes a near marginal profile, so that a small error in the measurement of η_i, or in the calculation of η_c can result in a significant error for $\gamma_{\max}$. With the finite flow shear, the linear growth rate of the toroidal drift-type mode can be also substantially changed by the next order equilibrium profile effect, (compared with the usual zeroth order ballooning calculation). The exact comparison between $\omega_{E\times B}$ and $\gamma_{\max}$ is thus very difficult and a more careful calculation is necessary. (iv) An explanation must be provided for the observation (d).

3. Weak magnetic shear model

Basic scenario: As mentioned earlier, this model starts from the observation that in the weak magnetic shear region around $q_{\min}$ position a discontinuity appears in the toroidal mode structure. The width and depth of the gap are closely related to the mode number, the diamagnetic drift shear, the flow shear, the q(r) curvature, and the pressure profiles etc., around $q_{\min}$ position [7]. Typically, the degree of the discontinuity increases as the wavelength becomes longer (which has a larger mode rational surface interval) and as the total shear from the diamagnetic drift and flow becomes larger. When the radial heat transport load is small at around $q_{\min}$ it can be handled by the short wavelength modes with a weak discontinuity degree, but with increasing heating power it becomes difficult due to the limitation in the heat transfer capability of the short wavelength modes by their large nonlinear saturation force. The long wavelength mode then becomes important, but in the corresponding increase of discontinuity degree. A blocking can thus occur in the radial heat transfer above a threshold power, which then leads to the local increase of T_i near $q_{\min}$ position and successively to the overall increase of inside ion temperature in the corresponding increase of the stabilizing effects by T_i/T_e, Shafranov shift, and electromagnetic effect etc. Due to this synergistic increase of η_c triggered by the local boundary temperature increase near $q_{\min}$, a steep T_i profile can be developed inside $q_{\min}$ position. The steady T_i profile will be then characterized by a marginal profile, $\eta_i \sim \eta_c$, with the increased boundary temperature near $q_{\min}$ position (unless the neoclassical transport becomes dominant or the plasma becomes MHD unstable).

Explanation of experimental observations: (a) As explained above, the power threshold appears since a small external heat load can be transferred by the short wavelength modes, which have a weak discontinuity degree. (b) The position of ITB foot is expected to be inside of $q_{\min}$ position, roughly shifted by the rational surface interval of the mode from which the gap effect becomes significant. (c) The discontinuity degree depends on the total sum of the diamagnetic and the flow shears, so can decrease or increase depending on the relative sign of these two shears. The degradation will start from the ITB foot, corresponding to the change of boundary temperature, and propagates inward. (d) We note first that an ambipolarity breakdown can occur due to the FLR effect in the short wavelength fluctuations driven transport. To see this, note first that for the model electric field $\mathbf{E} = E_y e^{ik_y y}\mathbf{y}$ with $k_y \rho_i \leq 1$ the gyrophase-averaged $\mathbf{E} \times \mathbf{B}$ velocity becomes

$$V_E(v_\perp) = V_{E0} J_0(k_y \rho_i), \tag{3}$$

where $\rho_i = m_i v_\perp / eB$, $V_{E0} = E_y/B$, and J_0 is the zeroth-order Bessel function. If we then estimate the particle flux from the quasilinear formula,

$$\Gamma_j = \langle \tilde{n} \tilde{v}_E^r \rangle_j, \tag{4}$$

where $j = i, e,$ and use the quasi-neutrality condition, $\tilde{n}_i = \tilde{n}_e$, it can seen easily that there occurs a difference in the electron and ion particle transport rate, like

$$\Gamma_i - \Gamma_e = [\Gamma_0(b_i) - 1]\Gamma_e < 0, \tag{5}$$

where $b_i = k_y^2 \rho_i^2$, Γ_0 is the zeroth order gamma function, and we have assumed the Maxwellian velocity distribution of ions and electrons. We see that the ion transport is reduced by $\Gamma_0(b_i)$, compared with the electron, so that a build up of ions in the gap region can occur when the transport is driven dominantly by the short wavelength modes, giving a local negative E_r field in front of the gap region or $q_{\min}$ position.

Question and check points: (i) There is a possibility of the generation of trapped ion mode-like modes in the weak shear region, which can destroy the local transport barrier. Since the trapped ion mode occurs near the maximum pressure gradient position, it is expected that the most steep gradient position will be not achieved in the $q_{\min}$ position, but may be inside of it. A more careful check is necessary. (b) From this model, it is expected that the final T_i profile will be characterized by $\eta_i \sim \eta_c$, unlike the $\mathbf{E} \times \mathbf{B}$ flwo shear model which predicts $\eta_i \gg \eta_c$. A check may be thus possible when we can determine exactly η_i and η_c, even though it is not so trivial.

4. Summary

A reconsideration has been presented about the two ITB models of the $\mathbf{E} \times \mathbf{B}$ shear flow and the weak magnetic shear models, to identify more clearly the strong and weak points of the models. In particular, a newly developed scenario has been presented for the weak shear model, showing that a reasonable explanation of some experimental observations is possible, even though a more quantitative check using more extensive numerical simulations is still necessary for the gap strength etc. (Some simulation results will be presented in this meeting [see Ref. 7]).

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