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Improved Models of β-Limit, Anomalous Transport and Radial Electric Field with Loss Cone Loss in Heliotron/Torsatron

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Abstract

Theoretical study is made on the physics mechanisms which determine the beta-limit, the anomalous transport, and the radial electric field and loss cone.

New theory is developed to analyze the stability boundary against the interchange mode in high-aspect-ratio toroidal helical plasmas, taking into account the transport processes. The stability β-limit is given at finite β-value, and the dependences on the plasma parameters and on the transport coefficient are investigated. It is found that the current-diffusive interchange mode is more important than the resistive mode in hot plasmas. The β-limit is predicted in the range of experimental observation for the anomalous transport. The dynamics of the pressure gradient and mode amplitude around this stability boundary are analysed. As the heating power is increased, the dynamics changes from the monotonous saturation, through the saturation with overshoot, and to the sawtoothing.

Using the mean-field theory approach of statistical physics for the microscopic current-diffusive interchange mode, the anomalous transport theory is developed. The expression of the thermal transport coefficient is obtained. The pressure gradient, not the temperature itself, enhances the transport coefficient. Comparison with experimental observations from various aspects is made, and the model explains experimental observations.

The method to obtain the self-consistent picture of the radial electric field E_r and the loss cone loss is explored. The structure of E_r and the loss cone are obtained, and it is confirmed that the direct ion loss makes E_r near edge more negative. Effects of other nonclassical loss are also evaluated.

1. Introduction

In order to understand the confinement and to perform the future optimization in Heliotron/torsatron configurations, the theoretical study on the physical mechanisms which determine the beta-limit and anomalous transport is necessary. Importance of interaction between the radial electric field and the loss cone is also recognized. In this article we present (1) the new theoretical results on the beta-limit of high-temperature plasmas in the presence of the transport processes, (2) the theory on the anomalous transport, which can explain experimental observations, and (3) the self-consistent picture of the radial electric field and the loss cone.

2. Finite-β Stability of Dissipative Plasma

We study the interchange instability by taking into account the transport processes such as the thermal conductivity χ, ion viscosity ν, current diffusivity λ and resistivity η. The reduced set of equations are used and a cylindrical model is employed. The case of high-aspect-ratio system with a magnetic hill is studied.

Linearlizing the basic equations, the eigenvalue equation is obtained.[1] It has been shown that the mode is always unstable when only the resistivity is taken into account. However, if other transport coefficients are kept, the critical beta value for stability, β_C, is found such that mode is stable below β_C as is shown in Fig.1. The stability condition is given as $D<D_C$, where

$$D_c = \min\left[\left(\frac{3\pi s}{2}\right)^2 \frac{\chi}{\eta} \left[\ln\{ \left(\frac{3\pi s}{2}\right)^2 \frac{1}{\nu\eta k_\theta^4} \} - 2\ln|\ln\{\frac{\chi\nu k_\theta^6}{64}\}| \right]^{-2}, \right.$$

$$\left. C s^{3/2} k_\theta^{-1/2} \lambda^{-3/4} \chi\nu^{1/4} \right] \qquad (1)$$

for given transport coefficient. (Notations are; $D=-\beta'\Omega'/2\varepsilon^2$, Ω' is the averaged curvature of the field line, $'\equiv d/d\rho$, $\varepsilon=a/R$, $\rho=r/a$, $k_\theta = m/\rho_1$, ρ_1: mode rational surface, m: poloidal mode number, $s=\rho\iota'$, ι: rotational transform, $\eta=\eta\tau_A/\mu_0 a^2$, $\lambda= \lambda\tau_A/\mu_0 a^4$, $\tau_A=R/v_A$, C is a numerical constant, and other notations are standard).

Equation (1) shows the dependence of β_c on the electron temperature T_e. When T_e is low and η is large, $\eta^5 D > k_\theta^2 s^4 \lambda^3$, the low-m resistive interchange mode (η-mode) determines the stability beta limit. As T_e increases and η is reduced, β_c increases for given value of χ. In the high T_e case, $\eta^5 D < k_\theta^2 s^4 \lambda^3$, the current diffusivity plays more important role in destabilizing the mode. The low-m current-diffusive interchange mode (λ-mode) determines β_c. It is also noted that, the larger values of χ and ν for higher T_e (as is observed in experiments) can also increase β_c in hot plasmas. The value of β_c is in the range of experimental data for presently-observed anomalous transport coefficients.

3. β-Limiting Phenomena

Evolutions of the pressure gradient and the mode amplitude near β_c are studied by taking into account the back-ground modification effect. Introducing the radial localization width of the mode around the rational surface, ℓ, we have the model equation describing the dynamics of the normalized pressure gradient D and the mode amplitude K as[2]

$$dD/dt = (D_{heat} - D) - KD/2(1+\hat{\gamma}), \qquad dK/dt = 2\hat{\gamma}K \qquad (2)$$

where $D = D/D_c$, $K = (\ell^2/\chi^2)\langle|\tilde{v}|^2\rangle$, $\hat{\gamma} = \gamma\ell^2/\chi$ (γ is the growth rate), and t is normalized to ℓ^2/χ. D_{heat} denotes the contribution of the external heating and corresponds to the gradient which would be sustained in the absence of this low-m mode activity. Note that $\gamma=0$ at $D=1$.

When heating power is increased and D_{heat} exceeds unity, the dynamical evolutions of D and K occur. The stationary solution of Eq.(2) is given by $(D^*, K^*) = (1, 2D_{heat} - 2)$. For given value of $z \equiv [\partial\hat{\gamma}/\partial D]$(at $D=1$), the critical heating rate is found. For the high heating case, $D_{heat} > D_c \equiv 1 + 1/(z-1)$, the sawtooth-like periodic relaxation of the pressure gradient is found associated with the repetitive bursts of the mode amplitude. Figure 2 shows the case of η-mode. The time average of the pressure gradient is limited to the critical value.

4. Anomalous Transport

The stability criterion for the interchange mode Eq.(1) indicates that λ-mode is most dangerous for the high-m mode (high-m η-modes are stabilized below the beta limit). The anomalous transport is determined by the high-m λ-mode[3]. For the high-m mode, the growth rate γ approaches to that of the fast interchange mode. The highest γ is evaluated as $\gamma\tau_A \sim \sqrt{D}$, for which the radial mode number satisfies $a^2 k_r^2 \sim s/\sqrt{\lambda\gamma\tau_A}$. The thermal transport coefficient is estimated by the formula $\chi=\gamma/k_r^2$. We here employ the mean-field theory of the statistical physics that this value of χ is identical to the thermal transport coefficient which governs the stability of the high-m modes. This closure assumption gives the result $\chi = (\lambda/\chi)D^{3/2}s^{-2}$. Noting the relation $\lambda/\chi \sim (\delta_s/a)^2$ (δ_s: collisionless skin depth), we have the formula of χ, in the dimensional form,

$$\chi = F(\rho)\{d\beta/d\rho\}^{3/2}\delta_s^2 v_A/R \qquad (3)$$

where $F=\{(N/2\ell)d(\iota\rho^4)/d\rho\}^{3/2}s^{-2}\rho^{-3}$, N is the toroidal pitch number and ℓ is the multipolarity.

The following results are obtained from this formula. (i) χ has the dimensional dependence of $T(0)^{3/2}/B^2R\sqrt{A}$ (A:mass ratio). (ii) χ has the radial dependence of $\{\beta' n(0)/n(\rho)\}^{3/2}$ and can be larger near the edge, though T itself is lower near edge (see Fig. 3). (iii) $\tau_E \sim F^{-0.4}A^{0.2}B^{0.8}n^{0.6}a^2RP^{-0.6}$ is predicted, which explains the so-called LHD-scaling, including the weak dependence on A and ι. (iv) The χ derived by heat pulse, χ_{HP} is larger than χ itself; In the region of $|\nabla T/T|>>|\nabla n/n|$, we have $\chi_{HP}/\chi=2.5$. It can also be shown that (v) the relative density fluctuation is smaller than that of potential fluctuation. These results explain the experimental observations[4].

5. Radial Electric Field and Loss Cone Loss

We develop a model to analyze the radial electric field E_r and loss cone loss in a self-consistent manner[5]. Using the formula of loss cone boundary as a functional of radial electric field, $\rho_*[E_r]$, the radial currant of the loss cone $\Gamma_{1c,i}$ is given [6]. Taking the neoclassical current Γ^{NC}[7] and other non-classical loss such as the charge exchange (cx), $\Gamma_{cx,i}$, we solve the equation

$$\Gamma_e^{NC} = \Gamma_i^{NC}+\Gamma_{1c,i}+\Gamma_{cx,i} \quad (4)$$

with the boundary condition $E_r \to 0$ at $r \to 0$. The radial electric field and loss cone are obtained simultaneously. Figure 4 illustrates the profile of E_r and the self-consistent loss cone boundary. It is found that E_r is more negative than the neoclassical prediction near the boundary. The effect of loss cone is small for $\rho<0.7$ for the CHS parameters. Experimental result on CHS indicates strong electric field suggesting the importance of the cx loss[8].

6. Summary

A progress was made in theoretical study on the physical mechanisms which determine the beta-limit, anomalous transport and the radial electric field and the loss cone. Results were obtained with analytical insights. In order to understand the confinement and to perform the future optimization in torsatron/Heliotron configurations, these results provide a firm basis, awaiting for the quantitative estimates and more careful comparison with experiments. We emphasize that these analyses can be extended to more general toroidal plasmas, and will be reported elsewhere.

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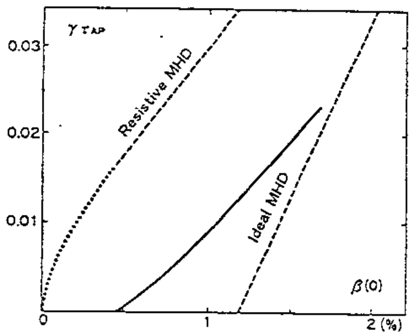

Fig.1 n=1 mode growth rate in H-DR. ($\eta=10^{-4}$, $\chi=5\times10^{-4}$.) Previous results are shown by dashed lines (resistive and ideal MHD calculations).

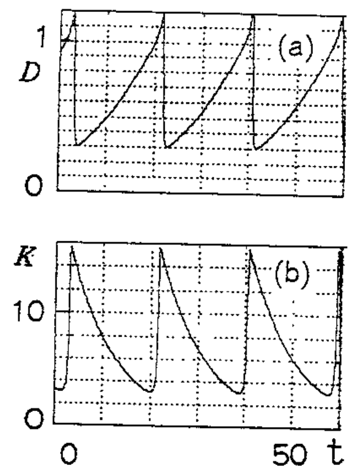

Fig.2 Temporal evolutions of pressure gradient (a) and amplitude (b). $D_{heat}=2.7$, $\ell^2 k_\theta^2=0.1$, and $z=2$.

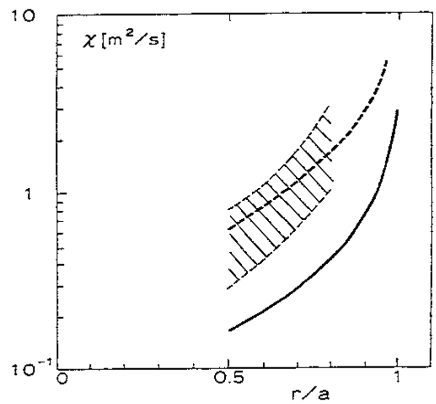

Fig.3 Predicted χ and experimental range. 4×Eq.(3) is shown by dashed line. ($p(r)$ profile is parabolic, $n(r)/n(0)=T(r)/T(0)$, B=2T, T(0)= 0.5keV, for Heliotron-E plasma.)

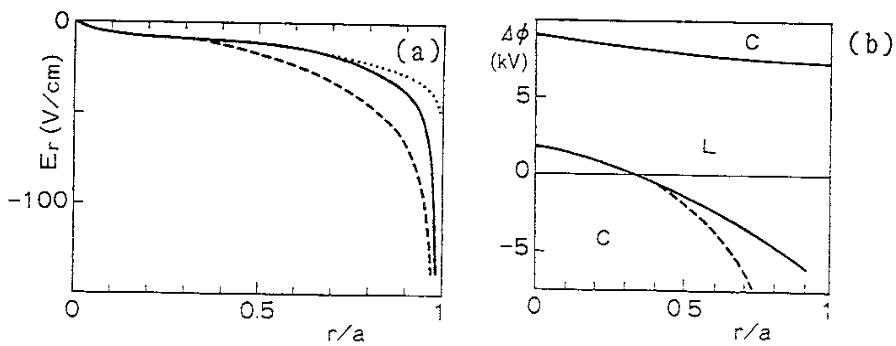

Fig.4 Radial profile of E_r for neoclassical result (dotted line), with fast ion loss effect(W_b= 18keV: solid line), and cx-loss added (dashed line) are shown in (a). Loss cone region is shown by L in (b) [$\Delta\phi=\phi(a)-\phi(0)$]. Self-consistent E_r profile is used for the solid line. Dotted line is for the assumption $E_r \propto r/a$. (Parameters are chosen for CHS experiment[8].)

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