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Theory of Anomalous Transport in H-Mode Plasmas

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Abstract

Theory of the anomalous transport is developed, and the unified formula for the L- and H-mode plasmas is presented. The self-sustained ballooning-mode turbulence is solved in the presence of the inhomogeneous radial electric field, E_r. Reductions in transport coefficients and the amplitude and decorrelation length of fluctuations due to E_r' are quantitatively analyzed. Combined with the E_r-bifurcation model, the thickness of the transport barrier is simultaneously determined.

Keywords: H-mode, Anomalous transport, Transport barrier, Radial
electric field shear, Current diffusivity, Tokamak,
Ballooning instability, Self-sustained turbulence

After found in ASDEX tokamak[1], the H-mode, i.e., the sudden improvement of the particle and energy confinement times during a discharge, has been observed in almost all tokamaks[2]. The reduction of the thermal conductivity χ, the energy flux per particle divided by temperature gradient, is most prominent near edge, and is referred to as a transport barrier. The H-mode phenomena is a generic nature of tokamak plasmas.

Transition physics has been advanced. A theory based on the bifurcation of the radial electric field, E_r, was proposed, taking up the interaction of the ion orbit loss and E_r[3]. The sudden change of E_r in a narrow edge region has been confirmed by experiments[4], and the external bias caused the H-mode[5]. Rapid change of ion loss at the transition was observed[6]. Elaboration of the model of the transition has followed[7-10]. It is now considered that E_r likely takes a large negative or positive value, the magnitude of which is given as $|X| \sim 1$ ($X = e\rho_p E_r/T$, ρ_p: poloidal ion gyroradius, T: temperature) in H-mode plasmas. The effects of E_r on the fluctuations and anomalous transport have then attracted attentions to explain the reduction of χ. The steep radial gradient of E_r can improve the stability and reduce the fluctuation level[12-16]. Though the influence of E_r on the fluctuation is qualitatively understood, the anomalous transport in the H-mode plasma was not yet explained. The understanding of the transport in H-mode ultimately requires that of the L-mode plasma simultaneously.

Recently, a new theory of the self-sustained turbulence and associated anomalous transport in the toroidal plasmas was developed[17,18]. It was found that one coefficient of the anomalous transport (current-diffusivity λ), which is driven by fluctuations, causes the instability while the other elements (ion viscosity, μ, and χ) suppress it. *The balance between them determines the self-sustained fluctuation and associated transport. The nonlinear instability was solved and the theoretical model of the L-mode transport was obtained.*

In this article, we apply this method to the tokamak plasma with the inhomogeneous E_r. The anomalous transport coefficient is obtained in an explicit form of the parameters which characterize the plasma profile. The typical scale of gradient of X, Δ, depends on the anomalous ion viscosity[19]. Selfconsistent solutions of Δ and χ are obtained. Improvement of the thermal conductivity in the H-mode plasma is explained. Change in the fluctuations is also analyzed.

We study a circular tokamak with the toroidal coordinates (r, θ, ζ). The reduced set of equations[20] is employed. The basic equations consist of the equation of motion, $n_i m_i (d(\nabla_\perp^2 \phi)/dt - \mu \nabla_\perp^4 \phi) = B^2 \nabla_\parallel J + B \nabla p \times \nabla (2r\cos\theta / R) \cdot \zeta$, generalized Ohm's law, $E + v \times B = J/\sigma - \nabla_\perp^2 \lambda J$, and the energy balance equation, $dp/dt = \chi \nabla_\perp^2 p$. Notations: m_i is the ion mass, n_i is the ion density, ϕ is the static potential, B is the main magnetic field, p is the plasma pressure, J is the current and σ is the classical conductivity. The $E \times B$ nonlinear interactions are renormalized in a *form of* χ, μ and λ. The detailed derivation was reported in *Ref.*[21]. The derivative d/dt is $\partial/\partial t + [\phi, \;]/B$, where $[\; , \;]$ denotes the Poisson bracket.

The doppler shift of frequency is offset for the homogeneous E×B rotation. Only the contribution of E_r' to d/dt is retained.

The ballooning transformation[22) is employed as $\tilde{p}(r,\theta,\zeta) = \sum_m \exp(-im\theta+in\zeta)\int\tilde{p}(\eta)\exp(im\eta-inq\eta)d\eta$, (q is the safety factor), since we are interested in microscopic modes. Eliminating $\tilde{\phi}$ and $\tilde{J}$ from basic equation, we have the eigenmode equation for $\tilde{p}$

$$\frac{d}{d\eta}\frac{F}{\hat{\gamma}+\Xi F+\Lambda F^2}\frac{d}{d\eta}\left[\hat{\gamma}+\omega_{E1}\frac{d}{d\eta}+KF\right]p + \alpha[\kappa+\cos\eta+(s\eta-\alpha\sin\eta)\sin\eta]p$$

$$-\left[\hat{\gamma}+\omega_{E1}\frac{d}{d\eta}+MF\right]F\left[\hat{\gamma}+\omega_{E1}\frac{d}{d\eta}+KF\right]p = 0. \qquad (1)$$

We use the normalization $r/a\to\hat{r}$, $t/\tau_{Ap}\to\hat{t}$, $\chi\tau_{Ap}/a^2\to\hat{\chi}$, $\mu\tau_{Ap}/a^2\to\hat{\mu}$, $\tau_{Ap}/\mu_0\sigma a^2\to 1/\hat{\sigma}$, $\lambda\tau_{Ap}/\mu_0 a^4\to\hat{\lambda}$, $\tau_{Ap}\equiv a\sqrt{\mu_0 m_i n_i}/B_p$, $\gamma\tau_{Ap}\to\hat{\gamma}$, and notation $\Xi=n^2q^2/\hat{\sigma}$, $\Lambda=\hat{\lambda}n^4q^4$, $K=\hat{\chi}n^2q^2$, $M=\hat{\mu}n^2q^2$, γ is the growth rate, $s=r(dq/dr)/q$, $F=1+(s\eta-\alpha\sin\eta)^2$, $\kappa\equiv-(r/R)(1-1/q^2)$ (average well), $B_p=Br/qR$, $\alpha=q^2\beta'/\varepsilon$, $\varepsilon=r/R$, a and *R for the major and minor radii*, $\beta=2\mu_0 p/B^2$, and $\beta'\equiv d\beta/d\hat{r}$. The parameter ω_{E1} denotes the effect of the radial electric field shear,

$$\omega_{E1} = \tau_{Ap}(dE_r/d\hat{r})(srB)^{-1}. \qquad (2)$$

If we neglect ω_{E1}, Eq.(1) *reduces to the transport-driven ballooning mode equation for the L-mode plasma*[18). The ideal MHD mode equation[22) is recovered by further taking $1/\hat{\sigma}=\hat{\lambda}=\hat{\chi}=\hat{\mu}=0$.

Equation (1) predicts that the current-diffusive ballooning mode has a large growth rate. It is assumed that $1/\hat{\sigma}=0$, for the plasma of our interest. [18]. The stability boundary of the nonlinear mode determines the relation between the anomalous transport coefficients $\{\hat{\chi}, \hat{\lambda}, \hat{\mu}\}$ and the plasma inhomogeneity $\{\beta'$,

E_r']. We here study the case that the ballooning mode is caused by the normal curvature, not by the geodesic curvature, i.e., $1/2+\alpha>s$. For the strongly localized mode, $s^2\eta^2<1$ and $\eta^2<1$, this eigenvalue equation is approximated in a from of the Weber type equation by neglecting the $dp/d\eta$ term as in Ref.[18,21]. We also treat the effects of ω_{E1} by the perturbation method. By these analytic simplifications, Eq.(1) with $\tau=0$ reduces to the equation

$$d^2p/d\eta^2 + (\alpha\Lambda/K)(1-(1/2+\alpha-s)\eta^2)p - M\Lambda(1+3s^2\eta^2)p + \mathcal{L}p = 0 \tag{3}$$

where the operator $\mathcal{L}$ is defined as

$$\mathcal{L}p = \omega_{E1}\left[\frac{K}{F}\frac{d^3p}{d\eta^3} - \Lambda(1+M/K)F^2\frac{dp}{d\eta}\right]. \tag{4}$$

The stability boundary is obtained by the perturbative method. Let $\{u_j\}$ be the j-th eigenfunction of the unperturbed equation ($\omega_{E1}=0$). The fundamental eigenmode u_0 and the *first* harmonics u_1 are expressed as $u_0=\xi^{1/4}\pi^{-1/2}\exp(-\xi\eta^2/2)$ and $u_1 = \sqrt{2/\pi}\,\xi^{3/4}\eta\exp(-\xi\eta^2/2)$, respectively. The odd and even parity modes are mixed by the operator $\mathcal{L}$ when $\omega_{E1}\neq 0$. Writing the eigenfunction as

$$p(\eta) = u_0 + \rho u_1 \cdots, \tag{5}$$

the eigenvalue is approximately given as

$$\frac{H^2}{\xi^2} \simeq 1 - \frac{\langle 0|L|1\rangle\langle 1|L|0\rangle}{\xi^2} \qquad (6)$$

where $H = H_0 N^2(1-N^4)$, $\xi^2 = H_0(1/2+\alpha-s)N^2\{1+C(s)N^4\}$, N is the normalized mode number $N^4 = n^4 q^4 \hat{\chi}\hat{\mu}/\alpha$, $H_0 = \alpha^{3/2}\hat{\lambda}\hat{\chi}^{-3/2}\hat{\mu}^{-1/2}$ and $C(s) = 3s^2(1/2+\alpha-s)^{-1}$. The most unstable mode satisfies $N^2 = 1/f(s)$ and $f(s)$ was given as $(1+2\alpha-2s)\sqrt{2+C(s)}$[18]. Substituting the eigenfunctions and N, the integrals $\langle 0|L|1\rangle$ and $\langle 1|L|0\rangle$ are performed. Equation (6) is rewritten as

$$H_0 = \left[1 + G_1(\alpha, s)\omega_{E1}{}^2\right](1+2\alpha-2s)f(s) \qquad (7)$$

where

$$G_1 = \left[\frac{9}{8}\left(1+\frac{4}{3\alpha f}\right) + \frac{25s^2}{4(1+2\alpha-2s)}\sqrt{\frac{2+C}{1+C}}\left(1+\frac{4}{3\alpha f}\right)\left(1+\frac{4}{5\alpha f}\right)\right]\frac{\alpha}{f^2} \qquad (8)$$

From Eq.(7), the anomalous transport coefficient in the presence of the inhomogeneous radial electric field is obtained as

$$\hat{\chi} = \frac{f(s)^{-1}\alpha^{3/2}(\hat{\lambda}/\hat{\chi})(\hat{\chi}/\hat{\mu})^{1/2}}{1 + G_1\omega_{E1}{}^2} \qquad (9)$$

The numerator of Eq.(9) is the transport coefficient in the L-mode, $\hat{\chi}_L$[18]. Equation (9) quantifies the effect of E_r' on the thermal conductivity, unifying the L- and H-mode plasmas. It is emphasized that the coefficients are given explicitly in terms of the equilibrium quantities. This is because the *self-sustained* turbulence is solved by our theoretical formalism. The suppression of the transport is prominent when $\omega_{E1} \sim 1/\sqrt{G_1}$. A noticeable reduction of χ occurs when ω_{E1} approaches unity.

The theory also predicts the change in the fluctuations. The relation $nq=(\alpha/\hat{\chi}\hat{\mu})^{1/4}N$ shows that poloidal mode number becomes larger as χ is reduced. *Using Eq.(9) and the estimate of* k_θ for the L-mode[18], we have

$$k_\theta{}^2 = \delta^{-2}\alpha^{-1}\left[\ 1 + G_1\omega_{E1}{}^2\ \right], \tag{10}$$

where δ is the collisionless skin depth. The radial correlation length of fluctuations, ℓ_r, is also reduced by the increment of X. Evaluation is given as $\ell_r{}^2 = \langle\langle k_r{}^2\rangle\rangle^{-1}$, where $\langle\langle k_r{}^2\rangle\rangle$ is the average of the squared radial wavenumber of fluctuations. We evaluate $\langle\langle k_r{}^2\rangle\rangle = \int n^2q^2s^2\eta^2p(\eta)^2d\eta\left[\int p(\eta)^2d\eta\right]^{-1}$. Equation (5) is substituted and yields $\langle\langle k_r{}^2\rangle\rangle=[n^2q^2s^2/2\xi](1+2\rho^2)$. Using the relation $\rho=\langle 1|\mathcal{L}|0\rangle/2\xi$, ℓ_r is given as

$$\ell_r{}^2 = \frac{2f(s)s^{-2}\xi\hat{\chi}\alpha^{-1/2}}{1+G_r(\alpha,s)\omega_{E1}{}^2} \tag{11}$$

$$G_r(\alpha,s) = \left[\frac{3}{4\sqrt{2}}+\frac{1}{\alpha f(s)}+\frac{23s^2}{8\sqrt{2}}\right]\frac{\alpha}{f(s)} \tag{12}$$

Fluctuation level is also reduced. The renormalized diffusivity has a relation $\chi \sim (r\tilde{E}/B)^2/(\chi n^2q^2)$[21], which gives the estimate, $\tilde{\phi}/B \sim \chi$. Using Eq.(9), we have

$$e\Phi/T \sim (\chi_L eB/T)\left[\, 1 + G_1\omega_{E1}^2 \,\right]^{-1}. \qquad (13)$$

The coefficients G_1 and G_r have a similar magnitude. The fluctuation level is reduced and the radial and poloidal correlation lengths become shorter as χ is subject to considerable reduction.

The thickness of the transport barrier, Δ, and χ are to be determined self-consistently. The radial derivative E_r' is estimated as E_r/Δ or $XT/e\rho_p\Delta$. It was shown that Δ reduces to the thickness of the source region (ρ_p) in the limit of $\mu \to 0$, and $\Delta \sim \sqrt{\mu/\nu_i}$ in the large μ limit[19,23] (ν_i is the ion collision frequency.) We take the interpolation formula

$$\Delta \sim \sqrt{\rho_p^2 + \mu/\nu_i} \qquad (14)$$

apart from a numerical factor of order unity. Substituting these relation into ω_{E1} and using the relation $\hat{\chi} \sim \hat{\mu}$[18,21], we have the self-consistent equation for χ as

$$\chi = \chi_L \left[1 + \frac{\beta}{2}\left[\frac{r}{\rho_p s}\right]^2 \frac{\alpha}{(1+\chi/\nu_i\rho_p^2)} X^2 \right]^{-1}. \qquad (15)$$

This equation shows that χ is reduced from the value in the L-mode by the increment of X. Unified expression for the L- and H-mode plasmas is obtained. The coefficient of X^2 in Eq.(15) depends on χ, because the gradient scale length is self-consistently treated. Figure 1 illustrates χ as a function of X for typical parameters. The order-of-magnitude reduction of

χ from L-mode value is demonstrated in the parameter range of $|X| \sim 1$.

It is a straightforward extension to study the influence of the curvature of E_r profile. The result is given as

$$\chi = \frac{\chi_L}{1 + G_1 \omega_{E1}{}^2 + G_2 \omega_{E2}{}^2} \qquad (18)$$

where $\omega_{E2} = (aE_r''/s^2 B)\tau_{Ap}$, $E'' = d^2 E_r/dr^2$, and $G_2 = (2/5)(\delta/a)^2$. Details will be given in a forthcoming paper.

In summary, we have developed the theory of the anomalous transport in tokamaks under the influence of the pressure gradient and inhomogeneous radial electric field. The marginal stability condition of the nonlinear ballooning mode was solved. The explicit relation of the transport coefficients $\{\mu, \lambda, \chi\}$ and the plasma inhomogeneity $\{p', E_r'\}$ was obtained keeping the geometrical factors such as q, R/a and magnetic shear. The anomalous transport coefficient and the thickness of the layer of the strong E_r in H-mode were self-consistently determined, by combining this theory with the electric field bifurcation model. This theory explains the plasma confinement in H-mode as well as L-mode simultaneously. The anomalous transport coefficient can be reduced by a factor of 1/10 in the edge region of the H-mode plasma in comparison with the L-mode.

This theory also predicts that the fluctuation level is reduced strongly when the radial electric field establishes in the H-mode. At the same time, the radial and poloidal correlation lengths become shorter. This theory could be tested by experiments not only on the macroscopic quantity such as the thermal conductivity (Eqs.(9), (16)), but also on the microscopic fluctuations (Eqs.(10), (11), (13)).

Compared to previous theories on nonlinear instability, our result confirms the Lorentzian form in the ω_{E1} dependence[12,13,16]. The main progresses are that the coefficients of $\omega_{E1}{}^2$ and $\omega_{E2}{}^2$ are explicitly given in terms of the plasma parameters, by solving the self-sustained turbulence: formula for the L- and H-mode confinement are obtained in a unified manner. These have become possible by the new theoretical framework, i.e., the E×B nonlinearity is renormalized in a form of diffusion operator and the mean-field approximation is employed.

We have taken various simplifications for analytic insight. Extension is necessary for the case that the mode is driven by the geodesic curvature. Analysis has been made for such a case of the L-mode plasma[21,24]. Difference was found in f(s), but other dependences were unchanged[24]. Numerical calculation is also necessary to study the limit of $|\omega_{E1}|>>1$ where the perturbation method does not hold. The change of the plasma profile can also explain the confinement improvement in the core region. Those extensions will be reported in future.

A nonlinear stationary solution is obtained in this letter. Connor has succeeded in reproducing our results on L-mode by use of the scale invariance technique[25], supporting the physics basis of our model, namely the renormalized diffusivity and the mean-field approximation. The present result (9) is obtained except for the numerical factor. Nonlinear simulation would give this coefficient and allows us to examine the validity of the ansatz in detail. Also necessary is the investigation of effects such as the diamagnetic drift for kinetic corrections, parallel flow or perpendicular compressibility. These research topics are open for future study.

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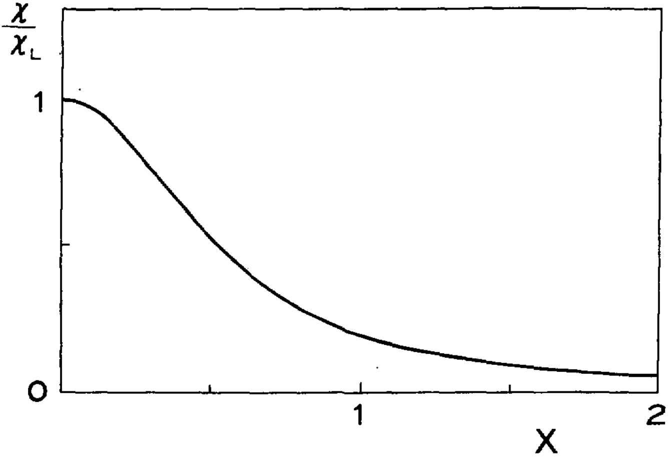
Figure Caption

Fig.1 Thermal conductivity χ, normalized to the L-mode value χ_L, is shown as a function of the normalized radial electric field, $X\equiv e\rho_p E_r/T$. Equation (15) is solved for the parameters of $n=2\times10^{19}$m-3, T=0.5keV, B=1T, a=1m, R/a=3, q=3, s=1 and α=1 for a pure hydrogen plasma.

Fig. 1



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