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Abstract

In this review article, we discuss key features of the transport phenomena and theoretical modelling to understand them. Experimental observations have revealed the nature of anomalous transport, i.e., the enhancement of the transport coefficients by the gradients of the plasma profiles, the pinch phenomena, the radial profile of the anomalous transport coefficients, the variation of the transport among the Bohm diffusion, Pseudo-classical confinement, L-mode and variety of improved confinement modes, and the sudden jumps such as L-H transition. Starting from the formalism of the transport matrix, the modelling based on the low frequency instabilities are reviewed. Theoretical results in the range of drift wave frequency are examined. Problems in theories based on the quasilinear and mixing-length estimates lead to the renewal of the turbulence theory, and the physics picture of the self-sustained turbulence is discussed. The theory of transport using the fluid equation of plasma is developed, showing that the new approach is very promising in explaining above-mentioned characteristics of anomalous transport in both L-mode and improved confinement plasmas. The interference of the fluxes is the key to construct the physics basis of the bifurcation theory for the L-H transition. The present status of theories on the mechanisms of improved confinement is discussed. Modelling on the nonlocal nature of transport is briefly discussed. Finally, the impact of the anomalous transport on disruptive phenomena is also described.

Contents

1 Introduction

It has been well known that the plasma loss process in toroidal magnetic confinement device is much faster than the expectation that is based on the binary collision of charged particles. This fast loss phenomenon has been known as the anomalous transport, and the detailed observations have been compiled in literature[1]. A main branch of the modern plasma physics that is related to the fusion research has been the research aiming at the resolution of the anomalous transport.

Though the transport phenomenon is still far from satisfactory understanding, some intelligence has merged related to the anomalous transport. In this article, we first review the progress in experimental knowledge, which are crucial for constructing the relevant theoretical modelling. Next, the theoretical framework is explained. In this article, we put an emphasis on the picture that the anomalous transport phenomena are expressed in terms of the local transport coefficients (more precisely, local transport matrix). Analyses have been developed in two ways: the magnitude of the diagonal elements (diffusivity, viscosity, thermal transport coefficient), and second, the influence of the off-diagonal elements. The former has been the main theme of theoretical researches to understand the global confinement characteristics. The latter has been thought to be essential in the pinch phenomena, and now is considered to give rise to the variety in the improved confinement.

Theories based on the fluctuations of drift wave instabilities are examined. The modelling in this line of thought can explain some features of anomalous transport, i.e., the degradation of confinement in high temperature plasma. However, there are couples of clear difficulties in explaining real plasmas. These difficulties requires to renew the picture of turbulence, which has been thought to be determined by the balance between the linear growth and the nonlinear stabilization. Progress in the turbulence theory is then discussed. A nonlinear mechanism was found to destabilize the modes. Turbulence is therefore dictated by the balance between the nonlinear stabilizing and destabilizing contributions. For this kind of states we use the word "self-sustained turbulence". An approach to treat the self-sustained turbulence is then discussed. The resultant modelling on the anomalous transport coefficient is shown. Many features of the anomalous transport phenomena are explained by the new progress in the theoretical modelling.

Next, the progress in the modelling of the improved confinement is reported. One of the key concepts is the role of the radial electric field. The L-H transition physics is explained. The suppression of the anomalous transport can also be discussed quantitatively, which became possible by the progress in the transport theory on the L-mode. The important role of the current profile is also shown, explaining the improvement by the high poloidal beta value and the current profile control (such as the lower hybrid waves, current ramp down).

Modelling based on the picture of the local transport coefficient is reported in this article, but the nonlocal treatment is also discussed. Essential nonlocal feature is presented, in connection with the structural formation of the transport barrier in the H-mode physics. Other direction of the nonlocal analysis is related to the transport of fluctuations and its influence of the transport coefficients. Finally the impact of the plasma transport on the disruptive phenomena is discussed.

2 Characteristic Features of Anomalous Transport

A schematic overview of historical development of the plasma confinement is given in Fig.1. The first impetus to proceed the confinement of high temperature plasmas was given by the finding of the Pseudo-classical confinement, in which the energy confinement time τ_E is empirically known to scale as $\sqrt{T_e}/n_e$, where T_e is the electron temperature and n_e is the electron density[2]. The range of plasma temperature in which this scaling law holds did not extend to the region of the thermonuclear fusion, and τ_E was found to degrade with temperature. The temperature was increased as a result of the efforts of high power heating, so that the confinement time was often compared to the heating power, rather than to the temperature itself, in experimental studies of energy confinement in tokamaks. The power degradation, i.e., the trend like $\tau_E \propto 1/\sqrt{P}$ was found to hold in a wide range of plasma parameters[3] (where P is the heating power). Then the plasma state with an improved confinement time was found. The most dramatic was the finding of the H-mode[4]. Following the H-mode, various kind of the improvement modes were found under the influences of the degassing of the wall (supershot), the pellet injection (pellet mode and PEP H-mode), the gas control in Ohmic plasma (improved Ohmic confinement, IOC), counter NBI heating, the lower hybrid wave current drive, the current ramp-down (high ℓ_i mode) and the high poloidal beta value (high $\varepsilon\beta_p$ mode) [5].

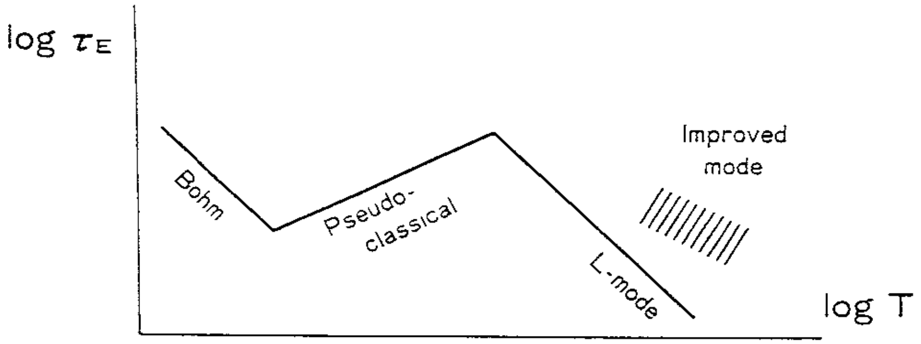


Fig.1 Schematic dependence of energy confinement time on plasma temperature

The universality of the L-mode transport suggests that it contains the essential feature of the anomalous transport in toroidal plasmas. The main feature is that the thermal conductivity χ (the ratio of the heat flux per particle to the temperature gradient) is an increasing function of the temperature gradient. Figure 2 shows the recent experimental data in JET tokamak[6], showing that the heat flux is the nonlinearly increasing function of the temperature gradient, i.e., χ is the increasing function of the temperature gradient. (This data also suggests that, in this situation, the heat flux becomes vary small (or vanishes) when the temperature gradient is absent.) This nature of χ is the origin of the power degradation of the global energy confinement time. This has also been discussed in connection with the comparison of the thermal conductivity in the stationary state χ^{eff} and that deduced from the propagation of the transient response of the plasma to the perturbation (such as after the sawtooth crash[7]) χ^{HP}. The observations that χ^{HP} is usually larger than χ^{eff} in tokamaks are considered to have the same physics basis to the power degradation of τ_E.

The anomaly appears not only for the thermal conductivity, but also for the particle and momentum transport coefficients. They are enhanced to similar magnitudes.

The additional aspect of the thermal transport coefficient in toroidal plasmas is that χ is usually larger near edge compared to the central part. Figure 3 illustrates a typical example of the radial profile of χ in the additional heating plasma (data from JFT-2M [8]). Though the temperature is lower near edge, χ is larger towards the edge. The radial profile is different to the trends of χ that χ is larger when plasma temperature is high in the L-mode plasmas. This presents one touch-stone for modelling the transport and may cast a key to understand the dependence of the energy confinement time on various geometrical factors.

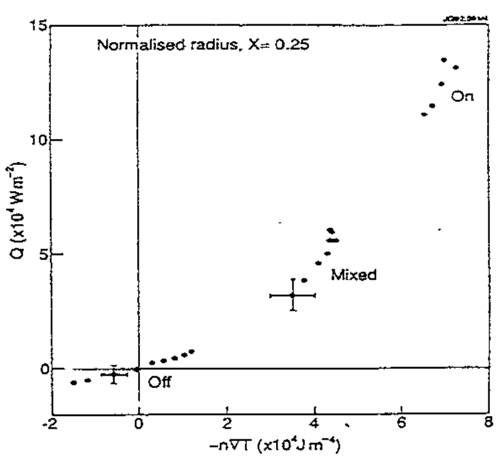


Fig. 2 Dependence of heat flux on ∇T (JET).

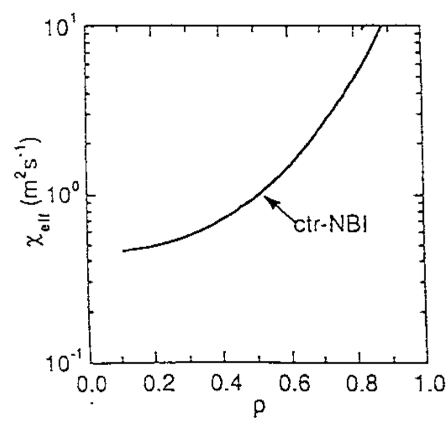


Fig.3 Radial profile of χ (JFT-2M).

The other characteristics of the L-mode plasma is the interferences between the different thermodynamical forces and fluxes. In addition to the fact that the particle diffusivity, the ion viscosity and thermal conductivity are enhanced in the anomalous transport, the interference is also important. Figure 4 is an example from the JIPP TII-U tokamak experiments [9]. The open symbol denotes the data under the neutral beam injection (NBI) heating, and the ion cyclotron range of frequency (ICRF) wave heating was super-imposed giving the data of closed symbols. The ion temperature is increased much due to the ICRF heating, and the rotation velocity is increased and density becomes higher as well. In this experiment, the ICRF heating does not supply the momentum and particle to the core plasma. The supply of the energy has caused the change in the velocity and density profiles. Influence between the particle and heat fluxes was also studied in heat pulse propagation [10], but that with momentum flux has not been analyzed.

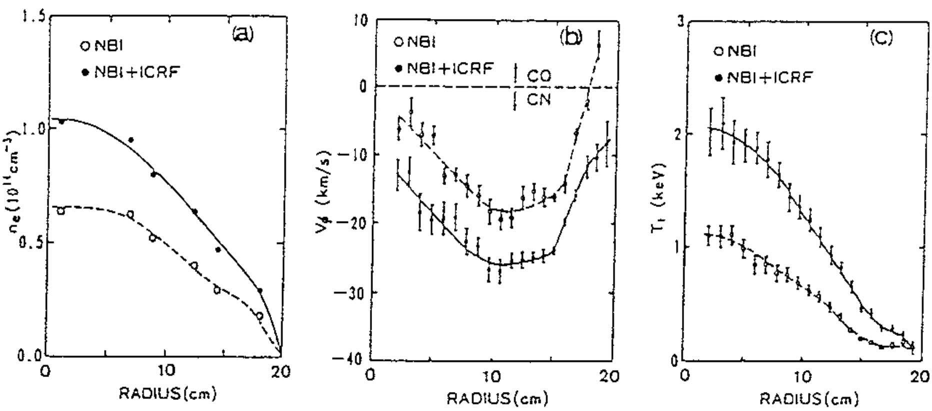


Fig. 4 Influence of additional ICRF heating on plasma profiles (JIPP TIIU)

The plasma has various variety in profiles associated with improved confinement. This casts a contrast, since the plasma temperature profile is known to respond very little to the change of heating profile in the L-mode plasma, which was known as the 'profile consistency (resilience)'[11]. Contrary to this resilience of the profile in the L-mode plasma, the change to the H-mode plasma is very drastic. The time of the transition is in the range of 100µsec or less, and is 1000 times shorter than the energy confinement time itself. The finding of the improved confinement modes implies that there are several thermodynamically stable states in plasma profiles, each of which is known by the name of L-mode, H-mode and other improved confinement modes, and the transitions between them, some of which is very rapid and other is slow, are possible. Figure 5 shows the profile of L-mode plasma and H-mode plasma [12].

These are the list of most prominent features of the anomalous transport in toroidal plasmas. Theoretical modelling should explain some of them simultaneously

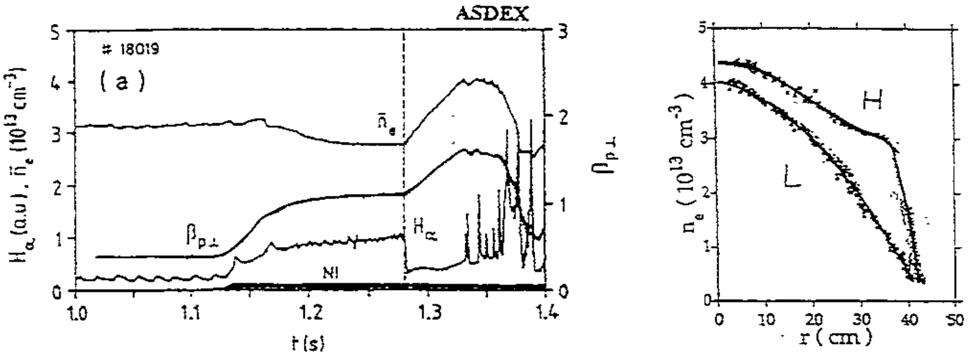


Fig.5 Transition to H-mode and density profile in H- and L-modes (ASDEX).

without contradicting others. Paradigm to explain these phenomena is that the anomalous transport is generated by the fluctuations[1.]. Recently there are emerging evidences that the low frequency fluctuations are directly related to the observed anomalous transport[13]. There arises the difference in the theory whether the electric fluctuations are responsible for the anomalous transport or the magnetic fluctuations are responsible. In this article we discuss the theoretical modelling based on the picture that the electric fluctuations are the origin of the anomalous transport. Magnetic turbulence and its relation to the L-mode and improved confinements are discussed very briefly.

3 Fluctuations and Anomalous Transport

3.1 Formalism and Transport Matrix

Physics picture of the fluctuation-driven transport has been reviewed in literature[1]. The geometry of the toroidal plasma and that for the local Cartesian coordinate are shown in Fig.6. Equilibrium plasma profiles are assumed to be constant on the magnetic surface. In the presence of the electric field fluctuations, which has the

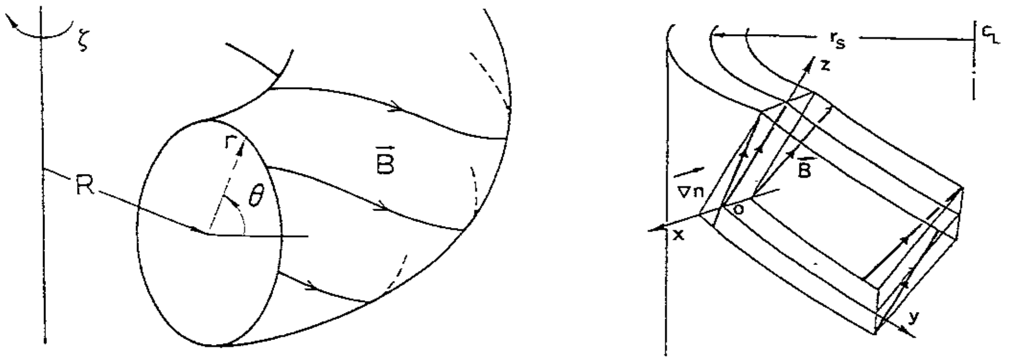


Fig. 6 Toroidal Plasma and local cartesian coordinate

component in the $\nabla n \times B$ direction, the plasma is subject to the $E \times B$ motion in the direction of ∇n. When the fluctuation is generated and decays with the characteristic time of $\tau_c = 1/\gamma$, the random walk with the step size of $1/k_\perp$ causes the diffusion as [1]

$$D \cong \gamma / k_\perp^2 \tag{1}$$

This expression is called as the mixing length estimate of the turbulent transport. The decorrelation rate γ and the scale length $1/k_\perp$ can depend on the plasma parameters. The task of theory is to determine the relation between the diffusion coefficient and fluctuation characters with the equilibrium plasma distributions. The explicit forms of (1) and results of various transport theory are discussed in the following subsections.

The other issue is the interference of various fluxes, i.e., the particle flux, momentum flux and heat flux. The inward pinch of particles stimulated the theoretical research [14], and the sign of wave frequency is related to the direction of the pinch[15]. As is demonstrated in Fig.4, the density gradient and the velocity shear can be increased by the increment of the heat flux. The relation between the fluxes and the thermodynamical forces are given in terms of the transport matrix **M**. The explicit form of **M** was derived by use of the quasi-linear estimate of fluctuation-driven fluxes in a quadratic terms of the fluctuating fields as [16-18]

$$\begin{pmatrix} \Gamma_e \\ J_\varphi / e \\ q_e / T_e \end{pmatrix} = \mathbf{M}_e \begin{pmatrix} X_{1e} \\ eE_\varphi / T_e \\ -T_e' / T_e \end{pmatrix} \tag{2-1}$$

and

$$\begin{pmatrix} \Gamma_i \\ P_{\varphi r} / m_i v_{Ti} \\ q_i / T_i \end{pmatrix} = \mathbf{M}_i \begin{pmatrix} X_{1i} \\ -2V_\varphi' / v_{Ti} \\ -T_i' / T_i \end{pmatrix} \tag{2-2}$$

where Γ_j and q_j (j=i,e) are the particle and heat fluxes, J_ϕ is the toroidal current, $P_{\phi r}$ is the radial flux of toroidal momentum, E_ϕ is the toroidal electric field, $'=d/dr$, the thermodynamical force X_1 is defined as $X_1 = -n'/n + e_\pm E_r/T + T'/2T - e_\pm B\omega/k_\theta T$, v_T is the thermal velocity, and $e_\pm = e$ for ions and $-e$ for electrons. Parameter ω and k_θ denotes the frequency and the poloidal wave number of the fluctuations. Symmetry of the matrices $\mathbf{M}_e$ and $\mathbf{M}_i$ was discussed[18]. It is also noted that ions and electrons has different transport matrices, and this framework may also explain the different behaviours of ions and electrons which were observed in experiments (for instance, high T_e mode or high T_i mode).

The expressions of the transport fluxes, Eq.(2), are not complete, because the fluctuation amplitude and wave numbers are explicitly included in **M** and are not given by the equilibrium quantities. However, the importance of the mixing of the transport is understood without the final result. The ratio of the diagonal elements and off-diagonal elements can be estimated, giving the results that the off-diagonal elements are the same order as the diagonal ones. This implies that the pinch term can be as large as the diffusive term. If one writes the flux as the sum of the diffusive term and the other, as is done in analyses of experimental data, in a form as (we choose the momentum balance equation for example) $P_{\phi r}/m_i n_i = -\mu^{eff} \nabla V_\phi + U^{eff} V_\phi$, the origin of the 'non-diffusive' pinch term $U^{eff} V_\phi$ is the off-diagonal elements. The estimates gives that the term $|\mu^{eff} \nabla V_\phi|$ can be the same order of $|U^{eff} V_\phi|$, that is, the pinch term has the considerable importance in determining the velocity and density profiles. This result corresponds to the observation on the pinch of particles and momentum.

It is possible to evaluate the impact of the anomalous transport on the toroidal plasma current. The interest on the Bootstrap current [19] motivated the influence on the current driving force. It was confirmed that, for the fluctuations which could be responsible for explaining the present-day cross-filed anomalous energy transport, the effect on the toroidal electric field is small [16,20].

The off diagonal term is also important in the energy balance. Let us consider the case that the plasma is subject to a strong energy supply and no particle and momentum are supplied within the magnetic surface of the interest. If one writes the relation between the heat flux and the temperature is as $q_i = -\overline{M}_{33} (\nabla T_i/T_i)$, the coefficient $\overline{M}_{33}$, which would be considered as the effective thermal conductivity in analyzing experimental data, is different from M_{33} in Eq.(2-2). In the limit of slab model, the coupling takes place in the matrix $\mathbf{M}_i$ between X_{1i} and T_i'. The explicit form was given for ions as

$$M_{ij} = n_i \int \frac{d\omega}{2\pi} \, v_{k\omega} \left(\frac{\omega}{k \, v_{Ti}} \right)^{i+j-2}, \quad v_{k\omega} = \left| \frac{k_\perp \tilde{\varphi}}{B} \right|^2 \frac{1}{k v_{Ti}} \Im\left(Z\left(\frac{\omega}{k \, v_{Ti}} \right) \right)$$

This result suggests that the off-diagonal terms M_{13} and $M_{31}(=M_{13})$ are of the same order of magnitude to the diagonal elements. In this situation $\overline{M}_{33}$ is given as

$$\overline{M}_{33} = M_{33} - \frac{M_{31}M_{13}}{M_{11}} - \frac{M_{32}M_{23}}{M_{22}} \qquad (3)$$

From the Schwartz inequality, the coefficient $\overline{M}_{33}$ is positive definite even in the presence of the off-diagonal elements. The other off diagonal elements (M_{12}, M_{21}, M_{23}, M_{32}) are in the higher order of r/R, and the mixing is caused by the toroidicity. It is noticed that these nature of the mixing, which happens between zero-th and second moments of the distribution function (density and temperature) in the slab plasma, is related to the Curie's principle (i.e., in the system with symmetries, the mixing occurs among the odd moments and among the even moments separately, but the mixing between odd and even moments does not take place)[21]. Toroidicity causes the mixing and asymmetry in the matrix.

The other important contribution which comes out of the interference of fluxes is that the bifurcation is predicted from the dependence of the plasma flux on the radial electric field. This has much stronger influence on the energy balance. The theory on the bifurcation is discussed in the later chapter.

3.2 Linear Response

Majority of theories on the anomalous transport was devoted to calculate the elements of the transport matrix for the fluctuations of drift wave frequency. The linear growth rate and the wave number of the most unstable mode have been employed for γ and k. This is based on the picture that the turbulence diffusion causes the damping on the mode as $Dk_\perp^2$ and the growth rate in the presence of the finite amplitude fluctuations, γ^{eff}, is given as $\gamma^{eff} = \gamma^L - Dk_\perp^2$, where γ^L is the linear growth rate. Figure 7 illustrates the relation of the mode growth rate with the diffusion coefficient. This picture is widely accepted in the vast literature discussing the fluctuation and transport based on the drift waves (including the trapped particle instability and eta-i modes). In the tokamak configuration, the trapped particles can destabilize the drift

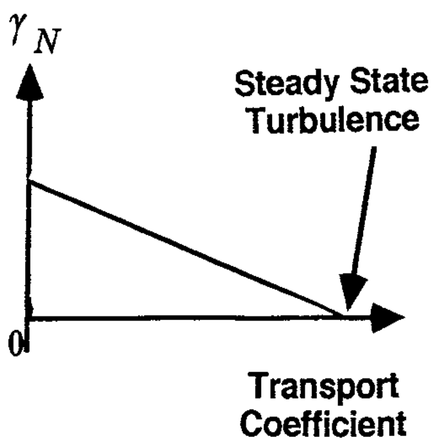


Fig.7 Quasi-linear picture of mode growth rate.

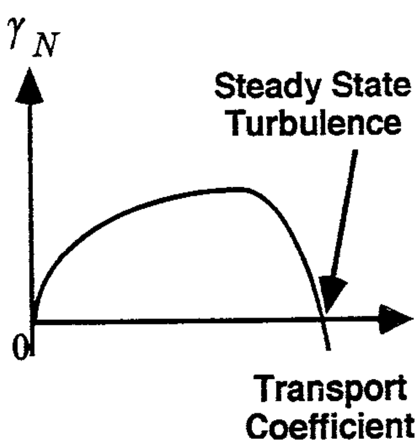


Fig.8 Mode growth rate for nonlinear instability

waves. The transport coefficients (i.e., the diagonal terms of the transport matrix) are estimated as

$$D = C \sqrt{\frac{r}{R}} \frac{\rho_i}{L_n} \frac{T_e}{eB} \tag{4}$$

where C is a numerical coefficient of the order unity (and can depend on geometrical factors in some theory), ρ_i is the ion gyro radius, L_n is the density gradient scale length, -n/n' [22]. Apart from the numerical coefficient C, the drift wave theory has given this characteristic result on the magnitude of the transport coefficients. The results in literature have differences in the coefficient C; some has dependence on temperature gradient, other on q profile. Though there are some differences, the essential feature of the theory which is based on the form of $D \cong \gamma^L/k_\perp^2$ is given by this equation.

The result is consistent to the power degradation of the energy confinement time. However, this form of thermal confinement contradicts to the observations that χ increases towards the edge, where the temperature is low. Additional discrepancy was noticed that the theory Eq.(4) predicts that χ is larger for the plasma with heavier ions, while experiments have shown that confinement is better for the case of heavier isotopes. (See Ref.[23,24] for detailed comparison with experimental data.)

3.3 Self Sustained Turbulence

The difficulty in the previous theories on the anomalous transport has urged a reconsideration about the state of stationary turbulence. Ohkawa has proposed a conjecture that in the high temperature plasmas the scale of micro-turbulence should be given by the collisionless skin depth, δ, giving the formula of $\chi = \delta^2 v_{Te}/qR$ [25]. This formula could have explained the nature of χ that χ is increasing towards the edge, and that χ increases by the increment of the plasma temperature. The scale of the collisionless skin depth does not appear from the most unstable linear mode of drift wave range of frequencies, so that a success of this model required the reconsideration of the turbulent state. The other progress in the theory of low frequency fluctuations is that the stability of drift waves is strongly affected by the existence of turbulence. The universal mode, which is known to be stabilized by the magnetic shear in the slab plasma[26], can be unstable if the back-ground turbulence level is high enough so that the electron parallel motion is impeded by the electron scattering [27]. Numerical simulations have shown that the shear-stabilized plasma becomes unstable to the modes in the range of drift waves in the presence of finite-amplitude fluctuations[28]. The inspection of the experimental data of the L-mode plasma transport has suggested that the beta-limit against the microscopic ballooning mode seems to have considerable influence on the transport as well[29]. Picture of the turbulence should be such that the stationary state is given by the balance between nonlinear destabilization and nonlinear stabilization. Figure 8 illustrates the situation providing the self-sustained turbulence.

In order to proceed to the new theoretical presentation for the turbulence, we start from a very simple level, i.e., the plasma is expressed in terms of the one fluid equation. This is much simplified compared to the fact that lots of kinetic process has been employed and distinction between ions and electrons has been analyzed in previous theories. However, new physics ingredients are that the theory properly treats the self-sustained turbulence, that the anomaly in transport coefficients (thermal conductivity χ, ion viscosity μ and electron viscosity μ_e) are treated simultaneously, and that the geometrical effects to cause toroidal instability are incorporated.

Figure 9 shows the growth rate of the microscopic ballooning mode in tokamaks as a function of the local pressure gradient. Above a threshold gradient, the ideal magnetohydrodynamic (MHD) mode can be unstable, and the criterion for it has been discussed in relation with the beta-limit of tokamaks [30]. Below the critical gradient against the ideal MHD mode, the microscopic ballooning mode can be unstable in the presence of the plasma dissipation. One mechanism of destabilization is the resistivity, and theories have been developed for the resistive ballooning mode [31]. We here emphasize that the dissipation associated with the electron viscosity can also destabilize the mode. Diffusion of parallel electron momentum can give rise to the diffusion of current [32]. The diffusion of the current generates the parallel electric field associated with the ballooning mode, which causes the insatiability. As is shown in the following, the anomalous diffusion of current can dominantly destabilize the microscopic ballooning mode. The fluctuations can enhance both the ion viscosity, thermal conductivity and electron viscosity. As is shown in Fig.10, the ballooning mode turbulence has stabilizing and destabilizing influences on the microscopic ballooning mode. Through this link of influences, the fluctuations develop to the state

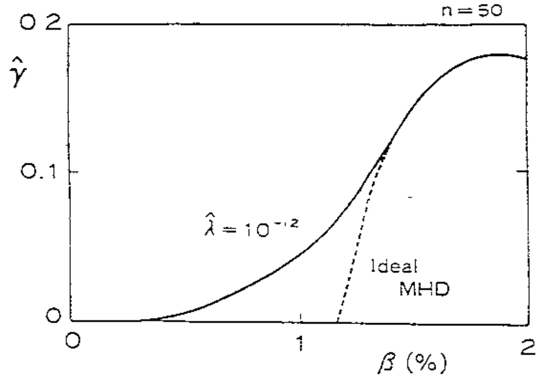


Fig.9 Growth rate of high-n Balloonijgn mode

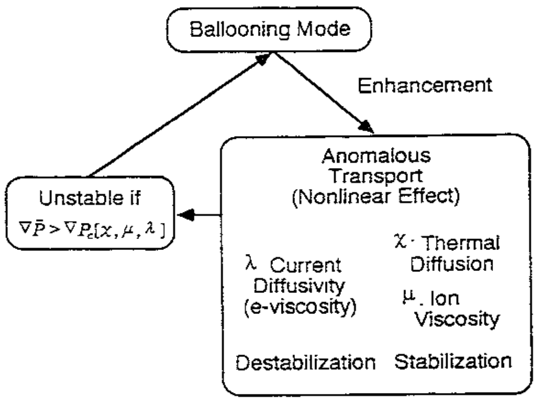


Fig.10 Scheme for self-sustained Turbulence

of self-sustained turbulence [33].

Qualitative analysis is performed starting from the set equations [34], which consists of the equation of motion, Ohm's law and energy balance equation. In the presence of the anomalous electron viscosity, the Ohm's law is rewritten as

$$E + v\times B = J/\sigma - \nabla\cdot\lambda\nabla J \qquad (5)$$

where J is the plasma current, σ is the conductivity and λ is the current diffusivity, which satisfies the relation $\lambda = (\delta/r)^2\mu_e$. We take the high-aspect ratio limit of circular tokamaks. The ballooning transformation from the (r, θ) coordinates to the η coordinate [35] is employed, since we analyze the microscopic modes. The dispersion relation for the microscopic ballooning mode is given in the presence of turbulence as [33,36]

$$\frac{d}{d\eta}\frac{F}{\hat{\gamma}+\Xi F+\Lambda F^2}\frac{d\varphi}{d\eta} + \frac{\alpha[\kappa+\cos\eta+(s\eta-\alpha\sin\eta)\sin\eta]\varphi}{\hat{\gamma}+XF} - (\hat{\gamma}+MF)F\varphi = 0 \qquad (6)$$

Terms Λ, X, and M represents the impact of the renormalized turbulence as $\Lambda = \hat{\lambda}n^4q^4$, $X = \hat{\chi}n^2q^2$ and $M = \hat{\mu}n^2q^2$. Ξ stands for the influence of the resistivity, $\Xi = n^2q^2/\hat{\sigma}$. Here normalization is used as $r/a \to \hat{r}$, $t/\tau_{Ap} \to \hat{t}$, $\chi\tau_{Ap}/a^2 \to \hat{\chi}$, $\mu\tau_{Ap}/a^2 \to \hat{\mu}$, $\lambda\tau_{Ap}/\mu_0 a^4 \to \hat{\lambda}$, $\tau_{Ap}/\sigma\mu_0 a^2 \to 1/\hat{\sigma}$ and $\gamma\tau_{Ap} \to \hat{\gamma}$. τ_{Ap} is the poloidal Alfven velocity $\tau_{Ap} = a\sqrt{\mu_0 m_i n_i}\,/\,B_p$, B_p is the poloidal magnetic field Br/qR, ε=r/R, $\beta = \mu_0 n_i(T_e+T_i)/B^2$, s=r(dq/dr)/q, $\kappa = -\varepsilon(1-1/q^2)$, $F = 1+(s\eta-\alpha\sin\eta)^2$, and $\alpha = -q^2R\beta'$ denotes the normalized pressure gradient. If one neglects the anomalous transport coefficient, Eq.(6) reduces to that for the resistive ballooning mode, and the ideal MHD mode equation is obtained by taking $1/\sigma=0$. The transport coefficient in terms of the fluctuation such as

$$\mu = \Sigma\frac{|k_{1\perp}\tilde{\varphi}_1|^2}{2B^2}\frac{k_{1\perp}^2}{\gamma_{u1}k_{1\perp}^2 + \frac{e^2B^2}{m_i m_e}\frac{k_{1/\!/}^2}{\gamma_{j1}} + \frac{iA_1 k_{1\theta}\nabla p_0}{B\gamma_{p1}}} \qquad (7)$$

where $\gamma_{u1} = \gamma(1) + \mu k_{1\perp}^2$, $\gamma_{j1} = \gamma(1) + \mu_e k_{1\perp}^2$, $\gamma_{p1} = \gamma(1) + \chi k_{1\perp}^2$, g(1) is defined as $\partial\tilde{y}/\partial t = \gamma(1)\tilde{y}$ $A\tilde{p} = \frac{B}{n_i m_i}\left(\nabla\frac{2r\cos(\theta)}{R}\times\hat{\zeta}\right)\cdot\nabla\tilde{p}$ and the suffix 1 denotes the background fluctuations. Other elements are given in literature [37].

The equation (6) constitutes the nonlinear dispersion relation. It can be shown that the growth rate behaves as

$$\gamma \propto \lambda^{1/5}$$

showing that even the small amount of the current diffusivity can give a large nonlinear growth rate [33,36]. This result confirms that the growth rate of the microscopic ballooning mode behaves, in the presence of anomalous transport, as is shown in Fig.8. Since the nonlinear interactions are renormalized in the coefficients μ, λ and χ, the stationary state satisfying the marginally stability condition (γ=0) gives the relation between the transport coefficients. We here note the fact that the Prandtl numbers, μ/χ and μ_e/χ, do not change much, compared to the magnitude of the transport coefficients itself, when the turbulence level is varied. The stability boundary for the least stable mode is given in terms of the pressure gradient and transport coefficients as

$$\alpha = f(s,\alpha)^{2/3}\hat{\mu}^{1/3}\hat{\chi}\hat{\lambda}^{-2/3} \tag{8}$$

where the coefficient $f(s,\alpha)$ stands for the influence of the magnetic shear.

This state is thermodynamically stable. When the fluctuation level is low and anomalous transport coefficients are smaller than those of Eq.(8), the mode amplitude grows. On the other hand, if the mode amplitude exceeds the criterion, the mode is stable and amplitude reduces.

3.4 Transport Coefficient in the L-mode Plasma

Using the level of self-sustained turbulence in Eq.(8), the anomalous transport coefficient in the L-mode plasma is obtained [33,37]. The Prandtl number is close to unity[37]. Taking the assumption that $\mu/\chi = 1$ and $\mu_e/\chi = 1$ hold, the anomalous transport coefficient is given From Eq.(8) as $\hat{\chi} = f(s,\alpha)^{-1}\,\alpha^{3/2}\,(\delta/a)^2$, or in the dimensional form as

$$\chi = \frac{q^2}{f(s,\alpha)}(-R\beta')^{3/2}\,\delta^2\,\frac{v_A}{R} \tag{9}$$

The function f is fitted as $0.4\sqrt{s}$ in the strong shear limit, and approximated as $f(s,\alpha) = (1+2\alpha-2s)\sqrt{\{2+6(s-\alpha)^2/(1+2\alpha-2s)\}}$ in the weak shear limit. Figure 11 illustrates the typical radial distribution of the anomalous transport coefficient.

This form of χ is consistent in various aspect of the L-mode transport characteristics, i.e.,

- degradation of τ_E by intense heating,

- large χ near the edge,
- improvement of τ_E by the heavier isotope,
- dependence of τ_E on the plasma current,
- weak dependence of temperature on the magnetic field,
- weak dependence of temperature profile on the heating profile,
- larger χ^{HP} than χ^{eff},
- μ is enhanced to the level of χ,

and so on. Detailed comparison by use of the transport code is reported in the article by Fukuyama et al in this conference[38].

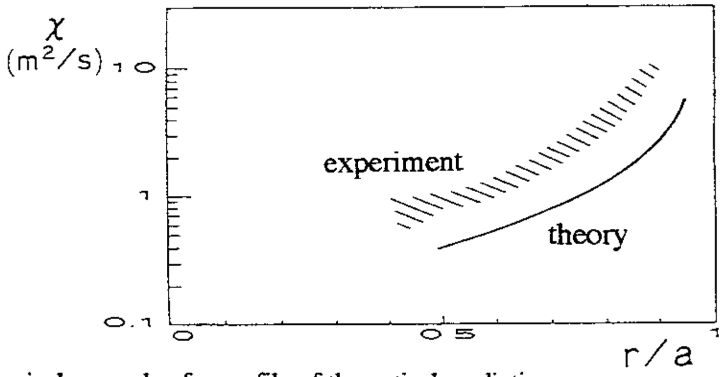


Fig.11 Typical example of χ profile of theoretical prediction

3.5 Fluctuations

The typical mode number of the mode, which is most strongly driven by the nonlinear interactions, is given as

$$k_{\perp} = h(s)/\delta\sqrt{\alpha} \tag{10-1}$$

showing that the characteristic scale length is given by the collisionless skin depth. The coefficient h(s) is about 0.1 for the parameter of $s \approx 1$ [36]. The fluctuation level is also given as

$$\frac{e\tilde{\varphi}}{T} \simeq \frac{eB}{T}\chi = \frac{q^2}{f(s,\alpha)}(-R\beta')^{3/2}\delta^2\frac{v_A}{R}\frac{eB}{T} \tag{10-2}$$

showing that relative fluctuation amplitude is larger near edge. (The difference of the fluctuation amplitude between core and edge is more prominent than that of the transport coefficient by the dependence of 1/T).

These results on transport coefficient and fluctuations supply the explanation for proper dependence on the pressure gradient and geometry. It is also noted that the argument based on the scale invariance method has confirmed this result [39]. Connor has extended the model in the case that the electron pressure term is more important in the Ohm's law than the parallel electric field. In such a case, Eq.(9) has different coefficient by the factor of $(v_e/v_A\sqrt{\alpha})$ [39]. This change in the factor preserves the nature that the newly obtained transport coefficient can be consistent in the above-mentioned aspects of the L-mode plasmas.

3.6 Connection to the Pseudo-Classical Confinement

This frame work of the self-sustained turbulence is applied to the low temperature plasma, and the connection between the L-mode and Pseudo-classical transport can be explained. When the plasma temperature is low, the driving source of the mode is Ξ rather than Λ in the nonlinear dispersion relation (6). If the temperature is low and the relation

$$\hat{\sigma} < \hat{\chi}^{-1/3}(a/\delta)^{4/3} \tag{11}$$

holds, the resistivity, rather than the current diffusivity, determines the growth of the mode. The analysis on the resistive ballooning mode [40] is recovered. In such a case, the transport coefficient is given as $\hat{\chi} = 2\alpha/\hat{\sigma}$, or in a dimensional form as [37]

$$\chi = \left(\frac{4\varepsilon r}{L_p}\right) \nu_{ei}\, \rho_{pe}^2 \tag{12}$$

where L_p is the pressure gradient scale length, β/β', ν_{ei} is the electron ion collision frequency and ρ_{pe} is the electron poloidal gyro radius. This formula is very close to the one obtained by Yoshikawa for the Pseudo-classical transport [41]. The change from

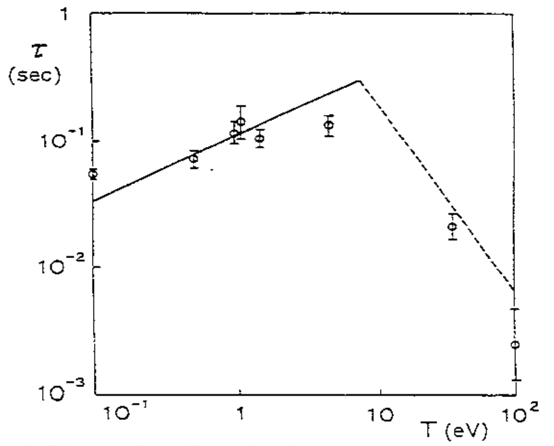


Fig. 12 Change from Pseudo-classical transport to L-mode transport is recovered.

Pseudo-classical confinement to L-mode confinement takes place at the condition Eq.(12). This result is compared to the experiments in the spherator [41]. For the parameters of experiments, the transition between Pseudo-classical mode and L-mode is predicted to occur at T=8eV from Eq.(11). A numerical coefficient of χ is adjusted so that the data in the low temperature limit is recovered. The transition is properly represented by this modelling on Fig. 12.

3.7 Bohm Diffusion

Although various mechanisms could give rise to the Bohm diffusion [42], the connection with Bohm diffusion can also be discussed along this line of thought. The relation between the fluctuation level and the diffusivity gives the upper bound of the anomalous transport. The upper bound of fluctuation level, $|\tilde{n}/n| \leq 1$, or $|e\tilde{\phi}/T| \leq 1$, gives the upper bound of χ, from Eq.(10-2), as

$$\chi \simeq \mu \leq \frac{T_e}{eB} \tag{13}$$

except a numerical coefficient of the order unity. When the temperature is decreased, the transport driven by the collisional mode is increased much. However, the transport coefficient is limited below the Bohm diffusion rate.

These results shows that the confinement characteristics changes from L-mode to Bohm confinement via Pseudo-classical confinement. The historical development of the confinement in Fig. 1 is now understood from the consideration of the self-sustained turbulence.

4. Physics of the H-mode

One of the most dramatic findings in the tokamak confinement is the H-mode. Figure 5 shows the transition from L-mode to H-mode, illustrating that the multiple states are allowed for given external conditions. A possible mechanism causing the multiple states of confinement was proposed by taking into account the effect of the radial electric field [43].

The basis of the modelling lies on the catasprophic relation between gradient and flux. The inspection on the experimental data suggests that the sudden change of the flux takes place at a certain threshold condition. The theoretical hypothesis is that the change of the flux occurs faster than the change of the profile; the profile change is the result of the change in the flux, (i.e., the transport coefficient). The cusp type catastrophe was proposed between the flux and gradients. It is noticed that this type of

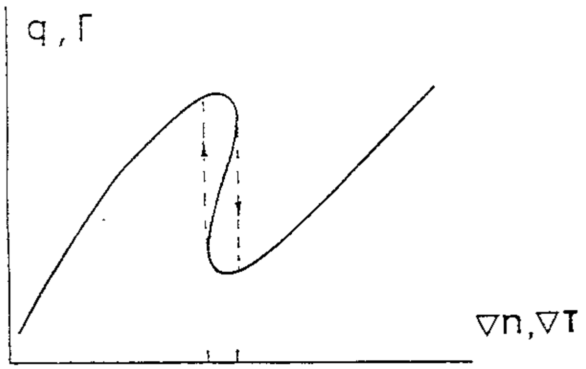


Fig. 13 Relation between gradient and flux, which can cause transition

catastrophe is possible if the thermodynamical force [∇T, ∇n] is imbedded in higher dimensional space, i.e., [∇T, ∇n, E_r]. The relation Γ [∇n, E_r] with the constraint

$$\Gamma_e [\nabla n, E_r] = \Gamma_i [\nabla n, E_r] \tag{14}$$

gives the form Γ [∇n] , which is projected in the lower dimensional space. The difference of the flux in electrons and ions is crucial in understanding this nature of the plasma bifurcation.

4.1 Bifurcation of Electric Field and Plasma Flux

The determination of the radial electric field requires the modelling of the bipolar component of radial particle flux. If a flux is caused by the momentum exchange between electrons and ions on the same magnetic surface, the momentum balance holds and the associated flux remains intrinsically ambipolar [44]. The anomalous particle flux, however, can be bipolar (for instance, the fluctuations propagates radially, exchanging momentum on different magnetic surface, or the inhomogeneity of fluctuations can lead to ambipolar flux). Other origins of bipolar flux are the orbit loss of ions (loss cone loss) Γ_i^{orbit}, the neoclassical flux such that the momentum dissipation by bulk viscosity and ripple loss Γ_i^{NC} and the flux generated by the momentum loss due to the charge exchange, Γ_i^{cx} . Neoclassical loss of electrons can be important if there are energetic electrons. We have

$$\Gamma_i - \Gamma_e = \Gamma_i^{NC} + \Gamma_i^{orbit} + \Gamma_i^{cx} - \Gamma_e^{NC} + \Gamma_a \tag{15}$$

where Γ_a denotes the bipolar part of the anomalous fluxes.

This equation really predicts the bifurcation of the radial electric field and plasma fluxes. The explicit form of the ion orbit loss is discussed in Refs.[43,45] as

$$\Gamma_i^{orbit} = \rho_p n_i \nu_i \varepsilon^{-0.5} \exp(-\xi X^2) , \qquad (16\text{-}1)$$

where ν_i is the ion collision frequency, $X=eE_r\rho_p/T$, and ξ indicates the effect of orbit squeezing due to the inhomogeneity of E_r (Ref.[45]). (Note that X is equal to the poloidal Mach number $V_pB/v_{Ti}B_p$ if one substitutes $V_p=E_r/B$.) Figure 14 illustrates the case that the anomalous bipolar flux is written as

$$\Gamma_a \propto \left[-\frac{n'}{n} + \frac{eE_r}{T_e}\right]$$

The jump of the total flux Γ, which is constrained by the condition Eq.(14), is predicted to occur at a critical point

$$\bar{\lambda} \equiv -\rho_p n'/n = \bar{\lambda}_c, \text{ and } \bar{\lambda}_c \simeq O(1) \qquad (17)$$

as is shown in Fig. 14(b). This example shows that the singularity of the transport property $\Gamma[\nabla n]$ can be explained by using a *continuous* function of $\Gamma[\nabla n, E_r]$. A cusp type catastrophe is derived.

An extension of the model is possible by considering the bulk viscosity. The bulk viscosity starts to reduce if the poloidal velocity exceeds a certain criterion. The flux generated by the bulk viscosity can be written as [45]

$$\Gamma_i^{NC} = -m_i n_i \nu_i q^2 V_p G(X)/eB \qquad (18)$$

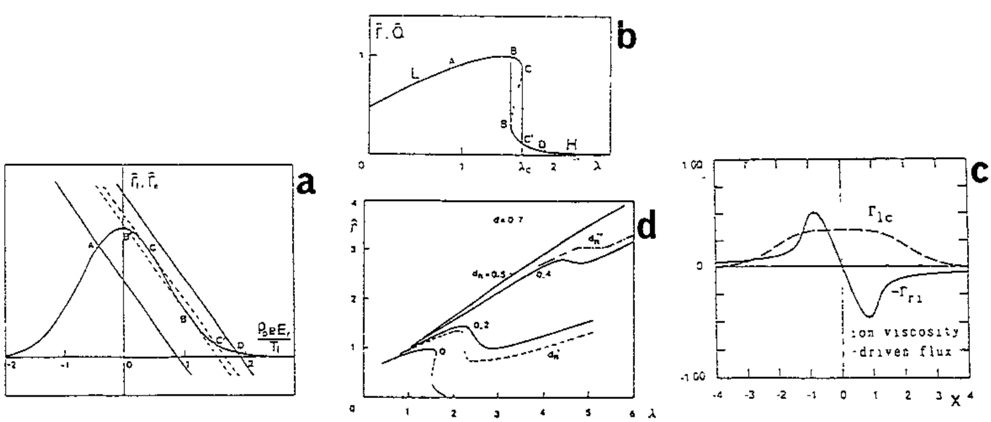


Fig 14 Ambipolar condition (a) and jump in flux (b). The cases with bulk viscosity (c) and neutrals (d)

where the function G(X) is unity for |X|«1 and behaves like $\exp(-X^2)$ (plateau regime) or X^{-2} (Pfirsch-Schluter regime) for |X|>1 (Refs.[46]). Figure 14(c) illustrates the balance of $\Gamma_i^{orbit} = \Gamma_i^{NC}$, confirming that the bifurcation can occur at a particular value of the edge gradient.

A variety of bifurcation has been theoretically deduced. The balance between the anomalous loss and orbit loss gives the bifurcation to the more positive E_r [43], and that between the ion neoclassical loss and orbit loss gives the bifurcation to the more negative E_r [45]. The former state may be called as H^+ and the latter as H^-. If one takes into account of the energetic electrons, the transition to the more positive sate is predicted [47]. Qualitative change in the nature of transition is predicted if the drag by the neutral particles exists. Figure 14(d) shows the relation Γ [∇n] for various values of the neutral particle density. When neutral drag exceeds a critical level, the hard transition of the flux disappears [48].

The proposal of an electric bifurcation was examined by experiments. D III-D and JFT-2M have confirmed the rapid change of the radial electric field in a narrow region near the plasma surface [49,50]. The radial electric field was found to become more negative in these experiments. The biasing experiments proved that the bifurcation occurs into both H^+ and H^- states [51,52], confirming the nonlinear response of Γ_i - Γ_e to X. JFT-2M also found that the change of ion loss from surface occurs faster than H_α decay at L- to H-mode transition [53], and supported the ion orbit loss model.

4.2 Transport Suppression

The gradient of the radial electric field influence the growth rate and mode amplitude of fluctuations. The picture of the H-mode, that the radial electric field changes much, revives the theoretical study on the influence of Er' on turbulence. The theoretical study was constructed in two ways; in one hand, the generation of the radial electric field is analyzed by taking into account the bipolar part of the anomalous flux. In the other hand, the ambipolar part of anomalous fluxes calculated, under the given influence of the inhomogeneous radial electric field. Combining these two procedures, the systematic study on the H-mode plasma will be possible.

Linear theories have shown that stability is improved by large value of |Er'|, through the mechanism of such as the enhanced ion Landau damping or the drift reversal of trapped particles [54]. Nonlinear theories have also developed based on the fluid turbulence and suggested a simple and useful criterion for the suppression of turbulence as [55-57]

$$\left|\frac{E_r' k_\theta}{B k_r}\right| \simeq \gamma^L \tag{19}$$

The curvature of the E_r profile is also effective in suppressing the turbulence.

The equation includes the parameters of the fluctuations, k_θ, and k_r. The explicit form of the thermal conductivity requires the solution of the turbulence, as was the case of the L-mode plasmas. The progress in the self-sustained turbulence has allowed to estimate the thermal transport coefficient in the H-mode plasma. It was obtained as [58]

$$\chi = \frac{\chi_L}{1 + H_1(\alpha,s)\omega_{E1}^2 + H_2(\alpha,s)\omega_{E2}^2} \tag{20}$$

where χ_L is the result in the L-mode theory, $\omega_{E1} = E_r'\tau_{Ap}/B$ and $\omega_{E2} = aE_r''\tau_{Ap}/B$. The coefficients H_1 and H_2 are explicitly given by the equilibrium quantities (Ref.[58] provides an explicit formula). The order estimate shows $H_1 \approx 1/\alpha$ ($\alpha \ll 1$) and $\approx \alpha$ ($\alpha \gg 1$). The term H_2 is of the order of $(\delta/a)^2$. The Lorentzian form of χ with respect to ω_{E1} was predicted in deriving Eq.(19) [55-57], and Eq.(20) provides a theoretical formula. The expression is obtained with the simultaneous explanation of the L-mode plasmas.

The fluctuation level is also predicted to reduce as is seen from Eq.(9). It can also be shown that the correlation length of the fluctuation becomes shorter. The correlation length d_θ is given as [58]

$$d_\theta^2 = \frac{d_\theta^2(L)}{1 + H_1(\alpha,s)\omega_{E1}^2 + H_2(\alpha,s)\omega_{E2}^2} \tag{21}$$

where $d_\theta(L)$ is that in the L-mode plasma. This formula shows that the correlation length becomes shorter due to the inhomogeneous radial electric field.

By the progress of the turbulence theory, the off-diagonal elements is also calculated. The generation of the radial electric field by turbulence has been studied as well [59,60]. Analytic theory has been developed. The qualitative form of Eq.(16-2) is confirmed. The numerical simulation has also been performed, and bifurcation of turbulence and radial electric field are observed [60].

4.3 Dynamics, Structure, and ELMs

This picture of the bifurcation of the transport coefficients predicts the hysteresis between ∇n and Γ (or between ∇T and q_r), which dictates the temporal and spatial structure of the edge transport barrier. The thickness of the transport barrier is an important parameter, since the gain in the energy confinement time is strongly influenced by the thickness. It is also worthwhile to study the transport nature in this highly nonlinear media, since the phase transition in matter can give rise to a variety in temporal and spatial bahaviour. It is shown that the hysteresis can generate an oscillation of the edge structure [61], and this oscillation is related to the small and frequent ELMs [62] in experiments.

The temporal and spatial dynamics was studied, by taking the responses in the density and radial electric field [61]. The continuity equation is written as

$$\frac{\partial n}{\partial t} = \nabla \cdot D(n; E_r)\nabla n \tag{22-1}$$

and the Poisson Equation combined with equation of motion, $\varepsilon_\perp \varepsilon_0 \partial E_r/\partial t = e(\Gamma_e - \Gamma_i)$, can be modelled as

$$\upsilon \frac{\partial E_r}{\partial t} = N(E_r; n) + \nabla \cdot \mu_\perp \nabla E_r \tag{22-2}$$

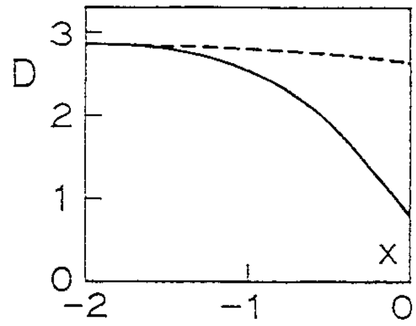
where the coefficient υ is of the order of $(\varepsilon/q)^2$, N stands for the nonlinearly in the bipolar flux as in Eqs.(16,18), and $\mu_\perp$ denotes the anomalous shear viscosity. It is shown that the anomalous transport coefficient D and $\mu_\perp$ are same order of magnitude. The fact that $\upsilon \ll 1$ shows that the radial electric field responds more rapidly than the density profile.

This set of equation is the time-dependent Ginzburg Landau equation with spatial diffusion. The set of equations are solved with the constant supply of flux from the core to edge, Γ_S. It was shown that edge plasma is in the L-state when Γ_S is large, and is in the H-state when Γ_S is small enough. The spatial distribution of the diffusivity is shown in Fig.15 for the H-state and L-state. When the H-state is realized, the transport coefficient changes from L-value to the H-value, with the spatial scale of variation Δ as

$$\Delta \simeq \sqrt{\frac{\mu_\perp}{\nu_i} + \rho_{pi}^2} \tag{23}$$

The ion poloidal gyro radius is the thickness of the source region for the orbit loss. The change of the electric field can penetrate into the core by the shear viscosity of ions [63]. This determines the thickness of the transport barrier. Since the value D takes the intermediate value between the two asymptotic limit of D which is obtained in the absence of the spatial diffusion for H and L-modes, the region of the variation of D is called as 'meso-phase'. Comparison is made on JFT-2M tokamak [64].

Near the boundary of Γ_S between these two stationary state, the self-generated oscillation is possible. Though Γ_S is constant in time, the outflux, which crosses at the plasma boundary, oscillates in time as is shown in Fig.16. The surface plasma oscillates from L-state to H-state periodically. This is an example that the hysteresis can generate oscillation for the boundary condition which is constant in time. This



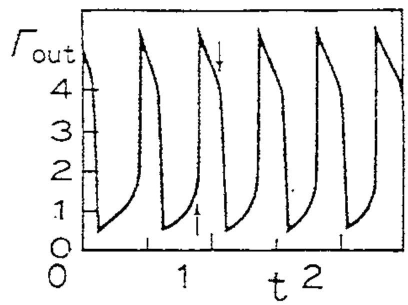


Fig. 15 Radial structure of D near edge in H- and L-states. Fig.16 Self-generated oscillation of out-flux.

oscillatory state is attributed to the small and frequent ELMs, which have been observed near the threshold condition for realizing the H-mode plasma. A classification has shown that ELMs near the threshold condition are distinguished from others [65]. There are other mechanisms which could lead to the transient decay of the transport barrier. The connection between giant ELMs and ideal MHD ballooning instability has also been investigated [66].

4.4 Confinement Improvement by Current Profile Control

The study on the L-mode and H-mode plasma has provided a clue to study the change in transport characteristics in other improved confinement state. We take two examples, i.e., the current profile control and the case of peaked density profile.

The theoretical result on the L-mode transport reveals the possibility to improve the transport by varying the current profile.

First, the thermal transport coefficient has the dependence of q^2. For the fixed total current, the profile of q inside of the plasma can be controlled by varying the current profile. If the current is reduced much faster than the resistive diffusion time, the q value is not increased in the core region at once. The change of χ does not instantaneously propagate to the core region. By this change of current profile, which is referred to as the increment of the internal inductance ℓ_i [67], the total energy confinement time is less affected compared to the total current itself. The ratio of τ_E to I_p, the confinement improvement factor, is predicted to increase almost linearly with ℓ_i.

Next, the coefficient $f(s,\alpha)$ stands for how the magnetic shear can affect the anomalous transport. If the shear is enhanced, the transport coefficient is reduced. It is also noted that the anomalous transport coefficient is reduced strongly in the very weak shear or negative shear region as is shown by Eq.(9). This confirms previous conjectures [68]. This reduction of χ is related to the second stability against the ballooning mode. As is shown in Eq.(6), the destabilizing potential of the ballooning mode has a dependence like ($\cos\eta + (s\eta - \alpha\sin\eta)\sin\eta$). The term $\cos\eta$ represents the normal curvature and the term $s\eta\sin\eta$ denotes the geodesic curvature [35]. If we expand near $\eta=0$, this potential behaves like $1-(1/2+s-\alpha)\eta^2$. The geodesic term stabilizes the mode if s is negative, as was discussed in relation with the second stability against the high-n ideal MHD ballooning mode [30].

The other mechanism of changing χ through modifying q is the change from magnetic hill to magnetic well. As is well known, the q value can be below 1 near the magnetic axis [69]. If the q value is less than one, the magnetic structure is no longer well but is the hill configuration. Then the interchange mode can be unstable, giving a larger transport coefficient [33]. If one elevates q(0) above unity, then the region of magnetic hill disappears, and the transport coefficient can be reduced.

These influences of the plasma current are related to the experimental observation of the improved confinement under the condition of the current-ramp-down [67], PEP (pellet-enhanced-performance) mode [68], high $\varepsilon\beta_p$ mode [70], and lower hybrid current drive [71]. Detailed comparison is given in Fukuyama [38] in this workshop.

4.5 Pinch and Peaked Profile Mode

The improvement of the confinement has also been observed associated with the density peaking [72]. One theoretical approach is to relate these observations to the eta-i mode instability [14,73]. The difficulty in explaining the L-mode plasma by the eta-i mode turbulence [24] induces to construct the new approach to explain the peaked density mode. A theoretical model has been developed to explain the spontaneous generation of the density peaking and improved confinement [74].

As is discussed in previous sections, the inward pinch is possibly generated by the radial electric field. The enhancement of the radial electric field is possible by the existence of the bipolar component of the flux. It was pointed out that the anomalous ion viscosity can work as the origin of the pinch of ions. The density gradient is sustained, in the absence of the radial particle flux, by the inhomogeneous radial electric field.

$$-\frac{2}{n_e}\frac{dn_e}{\partial u} = \left(\frac{a}{\lambda_n} - \frac{a^2}{2D_e}\langle S\rangle - C_1\right)\frac{I_0\left(u\sqrt{\nu_a/\nu_\mu}\right)}{I_0\left(\sqrt{\nu_a/\nu_\mu}\right)} + C_1 \qquad (24)$$

where $u=r^2/a^2$, $\nu_a = (1+Z)\,D_i/\rho_i^2$, $\nu_\mu = (1+1/Z)\,q^2R^2\mu_\perp/a^4$, $n/\lambda_n = -dn/dr$ at r=a, $\langle S\rangle$ stands for the particle source, and C_1 is the numerical coefficient to satisfy the boundary condition of n at r=a. This result indicates that the inhomogeneity of E_r is sustained even in the absence of the external momentum source. In the Ohmic plasma it is predicted that the radial electric field takes the form such that E_r' is positive. (It is noted that the rigid rotation of the plasma does not influence the transport, because the centrifugal force is negligibly small for the range of this analysis, and only the inhomogeneous part of the rotation is calculated.) The increment of the neutral density, <S>, causes the strong damping of rotation and radial electric field, and quench the pinch of particles.

This mechanism was analyzed in relation to the IOC mode [75], which is caused by stopping the gas-puffing. The established inhomogeneity of radial electric field then plays a role in reducing the ambipolar flux and thermal diffusion, as is predicted by Eq.(20). The transient response of the plasma confinement at the change from the counter-injection to co-injection (or vice versa) was experimentally studied on JFT-2M tokamak [8]. It was suggested that the inward flow is related to the observed radial electric field, which has been proposed theoretically [74,76]. The generation of rotation without momentum source is also evaluated experimentally [77].

4:6 Summary of Improved Confinement

Based on the theoretical studies described above, the region of expected improvement in transport and its origin are tabulated in Fig.17. The theoretical formula

Discharge Mode	Origin of Transport Reduction		
	Center	Core	Edge
H-mode	-	n_e pedestal	E_r'
VH-mode	-	↑ E_r'	↑
PEP H-mode	Hill to Well Low Shear	↑	↑
PEP L-mode	↑	-	-
High $\varepsilon\beta_p$	↑	Low Shear	-
LHCD	↑	-	-
High l_i	-	Reduced q	-
Density Peaking	-	E_r'	-

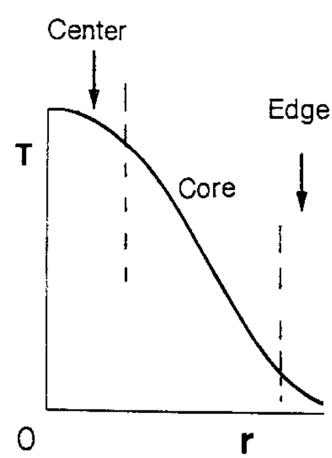


Fig.17 Location and origin of improvement for various confinement modes.

of χ is written as

$$\chi \propto \frac{q^2}{f(s,\alpha)} (\beta')^{3/2} \frac{1}{n'^{3/2}} \frac{1}{1+H_1\omega_{E1}^2 + H_2\omega_{E2}^2} \qquad (20')$$

The right hand side is expressed in a form of combination of four elements. The first element, q^2/f, represents the effect of the current profile and magnetic shear. The second shows the role of pressure profile. The third illustrates the effect of the density profile. The final term denotes the influence of the radial electric field inhomogeneity. There are variety in changing the transport coefficient. Depending on the way of changing either the current profile, density profile or the radial electric field, there arises a variety in the improved state of plasma confinement.

5. Note on Nonlocal Effect

The above argument is mainly developed that the transport coefficient is described by the local parameters which characterize the plasma profile. The analysis on the nonlocal nature of transport has also been developed.

The nonlocality was discussed in two ways in Sections 3 and 4. One is the exchange of wave momentum between different magnetic surfaces. This effect is modelled in a form of the ion shear viscosity and the current diffusivity. The other approach appears in the analysis of the H-mode phenomena. The orbit loss is determined by the radial electric field structure, so that the charge neutrality equation is not described by a equation describing the momentum balance on a magnetic surface, but the nonlocal nature is introduced through the term of Γ_i^{orbit}. The radial structure is obtained so as to provide the 'mesophase' near the plasma edge in Section 4.3.

There are other mechanisms which could introduce a nonlocal interaction of the plasma flux. One mechanism is the influence of the global magnetic instability on the anomalous transport [78]. Low-m mode can become unstable in tokamaks (such as m=2 tearing mode). The magnetic perturbation of the low-m MHD mode may pump the microscopic modes through nonlinear interactions. If this considerably enhances the turbulence level of the microscopic mode, the nonlocal nature would be essential for the tokamak profile; a quantitative result has not been deduced theoretically.

The other approach is found in the two-scale direct interaction approximation (TSDIA) method of plasma turbulence [79]. The spatial diffusion of the plasma would also be associated with the spatial diffusion of the fluctuations. Therefore, noises which could generate turbulence are transported from some region of the plasma to the fluctuation level by the radial diffusion of the fluctuations. A closed set of equations is derived for the fluctuation energy K_f and the dissipation density ε_f, and the coupled diffusion equation was solved. If the spatial inhomogeneity is considerably large, such as the strong edge turbulence, this nonlocal process would be important [79,80].

6. Role of Transport Process in Disruptive Phenomena

We finally note the important influence of the plasma transport on the disruptive phenomena. Sawtooth event is often discussed in relation to the study of the transport, i.e., the heat pulse propagation problem [7,10,81]. What is discussed here is the influence of the anomalous transport on the cause of disruptive phenomena, such as sawtooth and major disruption [82,83].

The intrinsic feature of the major disruption is the occurrence of the central temperature crash (thermal quench) preceded by a sudden burst of the helical deformation of the plasma column (magnetic trigger) [84]. This is also the case of sawtooth event [85]. The magnetic trigger phenomena is that the growth rate changes in time much faster than the time scale for the resistive instability, and requires a reconsideration for the onset of MHD instability [86]. The MHD theory has provided how the growth rate depends on the plasma parameters, concluding that the growth rate can change with the time scale that the equilibrium parameter develops. This clearly contradicts to the observations of the trigger phenomena.

The link between the current diffusivity, the mode growth rate and the turbulence amplitude provides a key to understand the magnetic trigger and crash mechanisms. The growth of the low-m mode causes the region of magnetic stochasticity, through the interaction with the toroidicity, if the mode amplitude exceeds a certain criterion [87]. The induced stochasticity leads to an enhanced electron viscosity. The enhanced electron viscosity then accelerates the mode growth rate. The increment of the growth rate causes larger mode amplitude, which further enhances the current diffusivity. This link of interactions, causes the explosive growth of the global mode, until the enhance ion viscosity and thermal conductivity stop the mode growth. The global stochastic region provides a rapid loss of plasma energy. Above the criterion, B_1 (the m=1 perturbation) greater than $B_c = \varepsilon s B/8$, λ is given as $\mu_0 \delta^2 v_{Te} D_M$, where D_M is the diffusion coefficient of magnetic field lines. The growth rate is given as [82,88] $\hat{\gamma} \simeq 10(\varepsilon s)^{4/5} \hat{\lambda}^{1/5}$, and the mode amplitude is given to show the explosive growth as

$$B_1 = \frac{B_c}{(1-\hat{t}/\tau_c)^{5/2}} \qquad (25)$$

where the coefficient τ_c is given as $1/\tau_c \simeq 5(\varepsilon s)^{4/5}(\delta/r_1)^{4/5}(v_{Te}/v_A)^{2/5}$. This model of the disruptive phenomena provides a new picture for the magnetic trigger and thermal quench. Firstly, Eq.(25) predicts that the time rate of the explosive phase, $\tau_c\tau_{Ap}$, is independent of the plasma temperature, i.e., rapid growth is possible even in very high temperature plasma. Second, the fast loss of energy can happen without a full magnetic reconnection of the core plasma. The energy quench and trigger is possible even by preserving central q-value below unity. Recent progress in the measurements on sawtooth [69] has provided discrepancies to the Kadomtsev reconnection model of the sawtooth [89], for which this model can provide resolutions [82,83,90].

7. Summary and Discussion

In this review article, we discussed the recent progress of theoretical modelling of the plasma confinement in toroidal plasmas. The experimental observations on the anomalous transport were summarized, for which theoretical modelling is required. The framework of the transport matrix was described, showing the importance of the off-diagonal elements. The estimation of the absolute value of the diagonal elements has long been investigated. Quasilinear and mixing length estimates of the transport coefficients have explained some part of the experimental observations, but there are undeniable discrepancies. A new modelling on the turbulence was developed, in which the nonlinear destabilization mechanisms and the nonlinear stability mechanisms balance so as to dictate the stationary turbulence. The application of this method was made to the microscopic ballooning mode, and explicit formula of the anomalous transport coefficient was obtained.

This new theory has provided a better understanding on the L-mode plasma confinement, and several mysteries (such as the radial profile and dependence on the ion mass and current profile of χ) were explained.

The modelling of the improved confinement was reviewed next. The bifurcation of radial electric field and the suppression of anomalous transport are presently accepted as working hypothesis. The unified view of the anomalous transport coefficient among L-mode, H-mode, and other improved confinement was presented. Progress was made in qualitative understanding of the anomalous transport.

Other topics such as the impact of the anomalous transport on the disruptive phenomena were also discussed. The plasma is full of disruptive events, including ELMs and momentum transfer events (MTE) [91], high beta collapse [70], in addition to disruption and sawtooth. The analysis on the link between the current diffusivity and various instabilities seems to provide a key for these disruptive phenomena. Further research is necessary in the direction of not only studying these phenomena for the tool to investigate transport [7,92,93], but also explaining these events by clarifying the role of the transport on them.

It looks that the modelling of transport phenomena has come to a new stage, in which a quantitative explanation of the anomalous transport will be possible from the first principle theory. The results, which were so far reported in this article, are presently still limited in applicability. For instance, the energy transport of ions and electrons must be treated separately, in order to analyze the high T_i mode and high T_e modes, a possible difference between heat pulses of ions and electrons [93], or the electron heat pinch phenomena [94]. The particle transport is not described in a manner that is consistent with the energy transport. The problems associated with impurities are not completed. Nonlocal effects need quantitative evaluation. The analysis on the scrape-off-layer has to be extended much, in order to clarify the boundary condition of the main plasma transport, and to find a solution for the divertor plasma[95]. Although there are still a lot of theoretical issues waiting for investigations, a large progress should be made in theoretical understanding of the transport phenomena in a near future.

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References

[1] Kadomtsev B B: in *Plasma Turbulence* (Academic press, New York, 1065),
Yoshikawa S: in *Methods of Experimental Physics* (Ed. Griem H R, Loveberg R H, Academic Press, New York, 1970) Vol.9, Chapter 8,
Liewer P: Nucl. Fusion **25** (1985) 543.
[2] Yoshikawa S: Phys. Rev. Lett. **25** (1970) 353.
[3] Goldston R J: Plasma Phys. Contr. Fusion **26** (1984) 87,
Yushomanov P, et al.: Nucl. Fusion **30** (1990) 1999.
[4] Wagner F, et al.: Phys. Rev. Lett. **49** (1982) 1408.
[5] Stambaugh R D et al.: Phys. Fluids **B2** (1990) 2941. See also
Hawryluk R J et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987) Vol.1, 51.
Mertens V et al.: Plasma Phys. Contr. Fusion **32** (1990) 965,
Keilhacker M and JET Team : Plasma Phys. Contr. Fusion **33** (1991) 1453,
[6] Keilhacker and JET Team: presented in *14th Int. Conf. Plasma Physics and Controlled Nuclear Fusion, Wurzburg*, (1992, IAEA), paper A-1-1.
[7] Callen J D and Jahns G L: Phys. Rev. Lett. **38** (1977) 491.
[8] Ida K et al.: Phys. Rev. Lett. **68** (1992) 182.
[9] Ida K et al.: Nucl. Fusion **31** (1991) 943.
[10] Gentle K W: Phys. Fluids **31** (1988) 1105,
Hogeweiij G M D et al: Plasma Phys. Contr. Fusion **33** (1991) 189,
de Haas J C M et al.: Nucl. Fusion **31** (1991) 1261,
Sipes A C C et al.: Nucl. Fusion **31** (1991) 1545.
See also Efthimion et al.: Phys. Rev. Lett. **66** (1991) 421.
[11] Coppi B: Comments Plasma Phys. Contr. Fusion **5** (1980) 261.
Goldston R J et al: in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987) Vol.1, 75,
Cordey J G and JET Team: in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987) Vol.1, 99.
[12] Wagner F and ASDEX Group: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 277.
[13] Wootton A et al: Phys. Fluids **B2** (1990) 2879,
Ji H et al: Phys. Rev. Lett. **67** (1991) 62.
[14] Coppi B and Spight C: Phys. Rev. Lett. **41** (1978) 551.
[15] Inoue S and Itoh in *Plasma Physics and Controlled Nuclear Fusion Research 1980* (IAEA, Vienna, 1981) Vol.1, 649,
Hazeltine R D et al: Phys. Fluids **24** (1981) 1164.
[16] Shaing K C: Phys. Fluids **31** (1988) 2249.
[17] Itoh S-I: Phys. Fluids **B4** (1992) 796.
[18] Balescu R: Phys. Fluids **B3** (1991) 564.
[19] Bickerton R J et al: Nature **229** (1971) 110.
[20] Itoh S-I and Itoh K: Phys. Lett. **A127** (1988) 267.
[21] Prigogine I: in *Introduction to Thermodynamics of Irreversible Processes* (2nd ed., Interscience, New York, 1961) 54.
[22] Adam J C et al: Phys. Fluids **19** (1976) 561,
Horton C W: *Basic Plasma Physics II* (ed. Galeev A A, Sudan R N, North Holland, 1984) Chapter 6.4,
Diamond P H et al: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.2, 9.
[23] Duchs D and JET Team: in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987) Vol.1, 325,
Taroni A et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1 93.
[24] Connor J W et al: Plasma Phys. Contr. Fusion **35** (1993) 319.
[25] Ohkawa T: Phys. Lett. **67A** (1978) 35.
[26] Ross D W and Mahajan S M: Phys. Rev. Lett. **40** (1978) 324.
[27] Hirshman S P and Molvig K: Phys Rev. Lett. **42** (1979) 648.
[28] Scott B D: Phys. Rev. Lett. **65** (1990) 3289.
Wakatani M et al: Phys. Fluids **B4** (1992) 1754.

Carreras B A et al: Phys. Fluids **B4** (1992) 3115.
[29] Connor J W and Taylor J B: Phys. Fluids **27** (1984) 2676.
[30] Dobrott D et al.: Phys. Rev. Lett. **39** (1977) 943
Connor J W et al.: Phys. Rev. Lett. **40** (1978) 396.
Lortz D and Nuhrenberg J: Phys. Lett. **68A** (1978) 49.
Coppi B et al: Phys. Rev. Lett. **44** (1980) 990.
[31] Chance M S et al: in *Plasma Physics and Controlled Nuclear Fusion Research 1978* (IAEA, Vienna, 1979) Vol.1, 677,
Sykes A et al: Plasma Phys. Contr., Fusion **29** (1987) 719.
[32] Schmidt J and Yoshikawa S: Phys. Rev. Lett. **26** (1971) 753.
[33] Itoh K, Itoh S-I and Fukuyama A: Phys. Rev. Lett. **69** (1992) 1050,
Itoh K et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper H-2-1.
Itoh K et al: Plasma Phys. Contr. Fusion **35** (1993) 543.
[34] Strauss H: Phys. Fluids **20** (1977) 1354.
[35] Connor J W et al: Proc. R. Soc. London **A365** (1979) 1.
[36] Yagi M et al: Phys. Fluids **B5** (1993) in press.
[37] Itoh K et al: 'Self-sustained turbulence and L-mode Confinement in toroidal plasmas' Research Report NIFS-219 (NIFS, 1993),
Itoh K et al: Phys. Fluids **B5** (1993) No.9 in press.
Itoh K et al: 'Prandtl number of toroidal plasma' Research Report NIFS-234 (NIFS, 1993).
[38] Fukuyama A et al: this workshop
[39] Connor J W: Plasma Phys. Contr. Fusion **35** (1993) 757.
[40] Carreras B A et al.: Phys. Rev. Lett. **50** (1983) 503.
[41] Yoshikawa S: Nucl. Fusion **13** (1973) 433.
[42] Bohm D: in *The Characteristics of Electrical Discharges in Magnetic Fields*, ed. Guthrie A and Wakerling R K (McGraw-Hill, New York, 1949) Chap.2 Sec.5.
[43] Itoh S-I and Itoh K: Phys. Rev. Lett. **60** (1988) 1269.
[44] Inoue S et al: Nucl. Fusion **19** (1979) 1253
Horton C W: Plasma Phys. **22** (1980) 345.
[45] Shaing K C et al: Phys. Rev. Lett. **63** (1989) 2639.
[46] Galeev A A and Sagdeev R Z: Sov. Phys. JETP **26** (1968) 233,
Stringer T E and Connor J W: Phys. Fluids **14** (1971) 2177.
[47] Itoh K and Itoh S-I: Nucl. Fusion **32** (1992) 2243.
[48] Itoh S-I and Itoh K: Nucl. Fusion **29** (1989) 1031.
[49] Groebner R J, et al: Phys. Rev. Lett. **64** (1990) 3015.
[50] Ida K et al: Phys. Rev. Lett. **65** (1990) 1364.
[51] Taylor R J and et al.: Phys. Rev. Lett. **63** (1989) 2365.
[52] Weynants R R et al.: Nucl. Fusion **32** (1992) 837.
[53] Miura Y et al.: Phys. Rev. Lett. **69** (1992) 2216.
[54] Timoveev A V: Sov. Phys. Tech Phys. 10 (1967) 1331,
Sanuki H: J. Phys. Soc. Jpn. **52** (1983) 511, Phys. Fluids **27** (1984) 2500.
Itoh S-I et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna, 1989) Vol.2, 23.
[55] Bigrali H et al.: Phys. Fluids *B2* (1989) 1,
[56] Shaing K C et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna, 1989) Vol.2, 13.
[57] Hassam A B: Comments Plasma Phys. Cont. Fusion **14** (1991) 275.
[58] Itoh S-I et al.: 'Theory of anomalous transport in H-mode plasmas', Research Report NIFS-226 (NIFS, 1993).
[59] Diamond P H et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper D-2-4.
Drake J et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper D-2-5.
[60] Carreras B A et al: Phys. Fluids **B5** (1993) 1795.
[61] Itoh S-I et al: Phys. Rev. Lett. **67** (1991) 2485.
[62] Keilhacker M, et al.: Plasma Phys. Contr. Fusion **26** (1984) 49,
Doyle E J et al.: Phys. Fluids **B3** (1991) 2300.
Zohm H et al.: Nucl. Fusion **32** (1992) 489,
[63] Yahagi E, et al.: Plasma Phys. Contr. Fusion **30** (1988) 995.
[64] Ida K, et al.: 'Thickness of the layer of strong radial electric field in JFT-2M H-mode plasmas', Research Report NIFS-215 (NIFS, 1993).

[65] Miura Y, et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 325.
Kamada H et al.: presented at US-Japan workshop on transient phenomena (1993).
Indication for the limit cycle oscillation is reported in Zohm H et al.: in *Controlled Fusion and Plasma Physics*, Proceedings of the 20th EPS Conference, Lisboa, 1993, Europhysics Conference Abstracts (European Physical Society, Frankfurt) Vol.17C, Part I, p.19.
[66] Burrell K H et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna, 1989) Vol.1, 193,
Ozeki et al.: Nucl. Fusion **30** (1990) 1425.
ELMy activity caused by the pressure-gradient-driven instability is analyzed in Fukuyama A et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper D-4-21
[67] Zarnstorff M C et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 109,
Simonen T C and D-III D Group: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper A-1-2,
JT-60 Group: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper A-1-3,
Lao L L et al.: Phys. Rev. Lett. **70** (1993) 3435.
[68] JET Team: in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna, 1989) Vol.1, 215,
Tubbing B J D et al.: Nucl. Fusion **31** (1991) 839,
Hugon M et al.: Nucl. Fusion **32** (1992) 33.
[69] Soltwisch H et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987) Vol.1, 263,
West W P, et al.: Phys Rev. Lett. **58** (1987) 2758,
O'Rourke J: Plasma Phys. Contr. Fusion **33** (1991) 289.
[70] Simonen T C et al.: Phys. Rev. Lett **61** (1988) 1720,
Navratil G A et al.: *in Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 209,
Ishida et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 195.
[71] McCormick K et al.: Phys. Rev. Lett. **58** (1987) 491,
Equipe Tore supra: in *Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna, 1993) paper A-1-4.
[72] Greenwald M, et al.: Phys. Rev. Lett. **53** (1984) 352,
Strachan J D, et al.: Phys. Rev. Lett **58** (1987) 1004,
Mori M et al: Nucl. Fusion **28** (1988) 1892.
[73] Gehre O et al.: Phys. Rev. Lett. **60** (1988) 1502.
[74] Itoh S-I: J. Phys. Soc. Jpn. **59** (1990) 3431.
[75] Soldner F X et al.: Phys. Rev. Lett. **61** (1988) 1105.
[76] Itoh S-I and Itoh K: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.2, p321.
[77] Ida K et al.: 'Observation of non diffusive term of toroidal momentum transport in the JFT-2M tokamak' Research Report NIFS-241 (NIFS, 1993),
Nagashima K, et al.: this workshop.
[78] Kadomtsev B B: Plasma Phys. Contr. Fusion **34** (1992) 1931.
[79] Yoshizawa A: Phys. Fluids **28** (1985) 3313.
[80] Sugama H and Wakatani M: J. Phys. Soc. Jpn. **61** (1992) 3116.
[81] Fredrickson E D et al.: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 559.
[82] Lichtenberg A J et al.: Nucl. Fusion **32** (1992) 495.
[83] Itoh K et al: Nucl Fusion **32** (1992) 1851.
[84] Wesson J: *Tokamaks* (Oxford, 1987) 178.
[85] JET Team: in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991) Vol.1, 437.
[86] Wesson J: in *Theory of Fusion plasmas* (CEC, Bolonia, 1987) p253.
[87] Mercier C: Sov J. Plasma Phys. **9** (1983) 82,
Lichtenberg A J: Nucl. Fusion **24** (1984) 1277.
[88] Aydemir A Y: Phys. Fluids **B2** (1990) 2135.
[89] Kadomtsev B B: Sov. J. Plasma Phys. **1** (1975) 389.

[90] Kurita G et al: J. Phys. Soc. Jpn. **62** (1993) 524.
[91] Osborn T et al.: presented at US-Japan workshop on Transient Phenomena (1993).
[92] Hanada K et al.: this workshop
[93] Ion heat pulse is reported by Y. Miura et al.: 'Ion heat pulse after sawtooth crash in the JFT-2M tokamak', Research Report NIFS-240 (NIFS, 1993).
[94] Petty C C et al.: Phys. Rev. Lett. **68** (1992) 52.
[95] Itoh S-I et al.: Plasma Phys. Contr. Fusion **32** (1990) 427.

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NIFS-234 K. Itoh, S.-I. Itoh, A. Fukuyama, M. Yagi and M. *Azumi, Prandtl Number of Toroidal Plasmas;* June 1993

NIFS-235 S. Kawata, S. Kato and S. Kiyokawa , *Screening Constants for Plasma;* June 1993

NIFS-236 A. Fujisawa and Y. Hamada, *Theoretical Study of Cylindrical Energy Analyzers for MeV Range Heavy Ion Beam Probes;* July 1993

NIFS-237 N. Ohyabu, A. Sagara, T. Ono, T. Kawamura and O. Motojima, *Carbon Sheet Pumping;* July 1993

NIFS-238 K. Watanabe, T. Sato and Y. Nakayama, *Q-profile Flattening due to Nonlinear, Development of Resistive Kink Mode and Ensuing Fast Crash in Sawtooth Oscillations;* July 1993

NIFS-239 N. Ohyabu, T. Watanabe, Hantao Ji, H. Akao, T. Ono, T. Kawamura, K. Yamazaki, K. Akaishi, N. Inoue, A. Komori, Y. Kubota, N. Noda, A. Sagara, H. Suzuki, O. Motojima, M. Fujiwara, A. Iiyoshi, *LHD Helical Divertor;* July 1993

NIFS-240 Y. Miura, F. Okano, N. Suzuki, M. Mori, K. Hoshino, H. Maeda, T. Takizuka, JFT-2M Group, K. Itoh and S.-I. Itoh, *Ion Heat Pulse after Sawtooth Crash in the JFT-2M Tokama;* Aug. 1993

NIFS-241 K. Ida, Y.Miura, T. Matsuda, K. Itoh and JFT-2M Group, *Observation of non Diffusive Term of Toroidal Momentum Transport in the JFT-2M Tokamak;* Aug. 1993

NIFS-242 O.J.W.F. Kardaun, S.-I. Itoh, K. Itoh and J.W.P.F. Kardaun, *Discriminant Analysis to Predict the Occurrence of ELMS in H-Mode Discharges;* Aug.1993