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Physics of Transport Phenomena in Magnetic Confinement Plasmas

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Abstract

The phenomena caused by the transport of the plasma across the magnetic filed in toroidal devices are surveyed, and theoretical models are reviewed. First topics is the plasma structure in a steady state. The recent development of the theory on the plasma transport driven by the microscopic turbulence is explained. The sudden change in confinement, such as the H-mode transition in tokamaks, is discussed next. The physics of the bifurcation of the edge plasma, based on the dynamics of the radial electric field, is discussed. Finally, the role of the anomalous transport on the disruptive phenomena is reviewed.

§1. Introduction

It has been well known, from the beginning of the experimental research on the plasma confinement, that the plasma loss process is much faster than the expectation which is based on the binary collision of charged particles. This has been known as the anomalous transport (Ref.1). The majority of the modern plasma physics related with the fusion research has aimed the resolution of the anomalous transport processes.

In the anomalous transport process, there are two characteristic features. One is the nature that the plasma pressure gradient itself generates the turbulence so as to impede to the high pressure gradient. Plasma pressure, which is high at the core and low near the surface, is determined by the heat flux and the transport coefficient. The analysys is required to determine the profile, turbulence and transport coefficient at the same time. The other feature is the mixing between the fluxes of the energy, momentum and mass and related gradients of plasma profiles; The plasma rotates without the external source of torque and that the outward energy flux can generate the inward particle flux. The recent development of the theory on the plasma transport driven by the microscopic turbulence is first explained in this review.

The confinement of the plasma changes abruptly, such as the H-mode transition in tokamaks, and is often associated by the pulsative loss (Ref.2). The transport near the plasma edge can change much by a slight difference in the plasma parameters. The physics of the bifurcation of the edge plasma transport are then discussed.

Finally, the role of the anomalous transport on the disruptive phenomena (Refs.3,4) is reviewed. The magnetic surfaces are known to become stochastic by the growth of the global MHD modes. The stochastization of the field line leads to the enhanced transport, which further destabilizes the MHD mode. This link can explain various features of the catastrophic events in disruptions.

This review tries to illustrate the generic natures of the transport process in magnetic confinement plasmas, by choosing examples; the reference is not exhaustive.

§2. Fluctuations and Anomalous Transport

Formalism

The physics picture of the fluctuation-driven transport has been reviewed in literatures (see for instance Refs.1,5). Figure 1 shows the toroidal plasma. In the presence of the electric field in the $\nabla n \times B$-direction, the plasma is subject to the $E \times B$ motion in the ∇n-direction. When the fluctuation is generated and decays with the characteristic time of $\tau_c = 1/\gamma$, the random walk with the step size of $1/k_x$ causes the diffusion as (Ref.5)

$$D \simeq \gamma / k_x^2 . \qquad (1)$$

This expression is called the mixing length estimate of the turbulent transport. As is shown in the following, the decorrelation rate τ and the scale length $1/k_x$ are dependent on the plasma parameters. This explains one typical feature, i.e., the plasma structure itself influences the transport coefficients.

The other characteristics is the interference between the fluxes of the mass, momentum and heat. The magnetic confinement plasmas are usually sustained by the energy source near the axis. The injection of the energy (such as RF heating) leads to the peaked density profile or generates the plasma rotation. Figure 2 shows the experimental observation, that the profiles of the number density n(r) and toroidal velocity $V_\phi(r)$ are sustained by the energy source at axis. The relation between the fluxes and thermal forces are given, using the transport matrix $\mathbf{M}$, the elements of which are given in a quadratic terms of the fluctuating fields, as (Refs.6,7)

$$\begin{pmatrix} \Gamma_e \\ J_\phi/e \\ q_e/T_e \end{pmatrix} = \mathbf{M}_e \begin{pmatrix} X_{1e} \\ eE_\phi/T_e \\ -T_e'/T_e \end{pmatrix} \qquad (2)$$

and

$$\begin{pmatrix} \Gamma_i \\ P_{\phi r}/m_i v_{Ti} \\ q_i/T_i \end{pmatrix} = \mathbf{M}_i \begin{pmatrix} X_{1i} \\ -2V_\phi'/v_{Ti} \\ -T_i'/T_i \end{pmatrix} \qquad (3)$$

where Γ and q are the particle and heat fluxes, J_Φ, and E_Φ are the current and electric field in the toroidal direction, $P_{\Phi r}$ is the radial flux of the toroidal momentum, $' \equiv d/dr$, (r: minor radius), v_T is the thermal velocity, and the thermodynamical force X_1 is defined as

$$X_1 = -n'/n + e_\pm E_r/T + T'/2T - e_\pm B\omega/k_\theta T \quad (4)$$

where $e_\pm$=e for ions and -e for electrons.

These relations between fluxes and gradients govern the mixing in the transport processes. Elements of $\mathbf{M}_i$ have the similar magnitude to each other (so as for $\mathbf{M}_e$), and the off-diagonal terms have considerable influence on the plasma profile. The impact on the density profile is discussed in Ref.8. It is also noted that the electric field E_r influences the energy transport. This is discussed later in connection with the H-mode.

Linear Response

Application of these formalism to hot plasmas has been done focusing on the drift waves[1]. The linear growth rate and wave number for the most unstable modes are employed for γ and k. In the tokamak configuration, the trapped particles can destabilize the drift waves. (The time-averaged curvature is unfavorable for the particles which are trapped in the weak-magnetic-field region.) The transport coefficient is estimated as

$$D = C\sqrt{\frac{r}{R}}\,\frac{\rho_i}{L_n}\,\frac{T_e}{eB} \qquad (5)$$

where C is a numerical coefficient of the order of unity. Recent transport theories based on the drift wave is given, for instance, in (Refs.1,9).

The characteristics of the L-mode confinement is the power degradation of τ_E (Ref.10), to which Eq.(5) is consistent. However, this form of χ contradicts to the observations that χ increases towards the edge in experiments, where the temperature is low.

Self-sustained Turbulence

The mode growth is easily influenced by the fluctuations (Refs.11-14), and γ and k would be modified from those for the linear modes. In the following, we describe the recent development in the self-sustained turbulence and anomalous transport after Ref.14. The plasma transport process, in one hand, enhances the mode growth through the current diffusivity (i.e., the electron viscosity), and at the same time stabilizes it through the thermal conductivity and ion viscosity. The self-sustained state is determined by the balance between the mode amplitude and transport coefficients.

We employ the reduced set of equations and keep the current diffusivity term in Ohm's law,

$$E + v \times B = J/\sigma - \nabla^2 \lambda J, \qquad (6)$$

where σ is the conductivity and λ is the current diffusivity (Ref.16). The ballooning transformation (Ref.17) is applied. The current diffusivity, not the resistivity, is the mechanism to destabilize the pressure driven instabilities which are relevant for the anomalous transport process. The growth rate of the short wave-length mode, is given by $\hat{\gamma} \simeq \hat{\lambda}^{1/5}(nq)^{4/5}\alpha^{3/5}s^{-2/5}$. [Notations are: $\alpha=q^2\beta' R/a$, $s=rq'/q$, β is the pressure divided by the magnetic pressure, and $\beta' \equiv d\beta/d(r/a)$. Normalizations are: $\chi\tau_{Ap}/a^2 \to \hat{\chi}$, $\mu\tau_{Ap}/a^2 \to \hat{\mu}$, $\tau_{Ap}/\mu_0\sigma a^2 \to 1/\hat{\sigma}$, $\lambda\tau_{Ap}/\mu_0 a^4 \to \hat{\lambda}$, $\tau_{Ap} \equiv Rq/v_A$, $\gamma\tau_{Ap} \to \hat{\gamma}$, v_A being the Alfven velocity.] All the cross field transport coefficients are driven by the fluctuations.

The condition for the stationary state is given as $\alpha^{3/2}\hat{\lambda} = f(s)\sqrt{\hat{\mu}}\hat{\chi}^{3/2}$ where $f(s) \simeq \sqrt{6}s$ or 1.7 ($s \to 0$). We express $\hat{\chi}$ in terms of the Prandtl numbers $\hat{\mu}/\hat{\chi}$ and $\hat{\lambda}/\hat{\chi}$. The ratios $\hat{\lambda}/\hat{\chi}$ and $\hat{\mu}/\hat{\chi}$ are given as $\hat{\lambda}/\hat{\chi} = \delta^2/a^2$ and $\hat{\mu}/\hat{\chi} \simeq 1$ for electrostatic perturbations (Ref.7). The formula for χ is given in an explicit form as

$$\chi = f(s)^{-1}q^2(R\beta'/r)^{3/2}\delta^2 v_A/R. \qquad (7)$$

where δ is the collisionless skin depth. The typical perpendicular wave-number of the most unstable mode satisfies $k_\perp\delta \simeq 1/\sqrt{\alpha}$. The typical correlation time of the mode is estimated to be $\tau_c = 1/\gamma$, $\gamma \simeq \sqrt{\alpha/6}\,s(v_A/qR)$.

This form of χ is consistent with the experimental results known for the L-mode (Ref.1). For instance, the prediction on τ_E is consistent with the L-mode scaling law (Ref.10). Detailed comparison is given in Ref.14, and the future study in application of the data-analysis is required.

§3. Physics Picture of H-Mode

One of the most dramatic findings in recent plasma confinement experiments was the H-mode (Ref. 2). Figure 3 shows the transition from L-mode to H-mode (Ref.18). It has shown that multiple states are allowed for given external conditions, that typical gradient lengths can be disconnected from the minor radius, and that it has a rapid time scale for the transition. A possible mechanism of the multiple state of confinement was proposed by taking into account the effect of the radial electric field (Ref.19). The field can be multi valued by the direct orbit loss.

Bifurcations of Electric Field and Plasma Flux

The stationary solution of the radial electric field E_r is obtained by solving the charge neutrality equation, $\Gamma_e=\Gamma_i$, where

$$\Gamma_i = \Gamma_i^{NC} + \Gamma_i^{orbit} + \Gamma_{icx} + \Gamma_{i,a} , \qquad (8\text{-}1)$$

$$\Gamma_e = \Gamma_e^{NC} + \Gamma_{e,a} . \qquad (8\text{-}2)$$

These equations consist of the neoclassical fluxes (denoted by the superscript of NC), the direct ion orbit loss flux (Γ_i^{orbit}), the charge exchange contributions (Γ_{icx}), and that driven by the anomalous transport (Γ_a).

The explicit form of the ion orbit loss is discussed in Refs.(19,20) as

$$\Gamma_i^{orbit} \simeq \rho_p n_i \nu_i \varepsilon^{-0.5} \exp\{-\Xi X^2\} \qquad (9)$$

where ν_i is the ion collision frequency, $\varepsilon = a/R$, Ξ indicates the effect of orbit squeezing due to the inhomogeneity of E_r (Ref.21), and $X = eE_r\rho_p/T$. (X is equal to the poloidal Mach number $V_pB/v_{Ti}B_p$ if $V_p = E_r/B_t$.) Figure 4(a) illustrates the case study that the bipolar part of the anomalous flux,

$$\Gamma_{a,e} - \Gamma_{a,i} \propto (-n'/n + eE_r/T_e). \qquad (10)$$

The jump of flux Γ is predicted at the critical gradient

$$\bar{\lambda} \equiv \rho_p n'/n = \lambda_c, \quad \text{and } \lambda_c \sim O(1) \qquad (11)$$

as is shown in Fig.4(b). This example shows that the singularity of the transport property $\Gamma[\nabla n]$ can be explained by using a <u>continuous</u> function of $\Gamma[E_r]$ (Ref.19).

An extension of the model is possible by considering the bulk viscosity contribution in Γ_i^{NC}. The bulk viscosity generates the flux as

$$\Gamma_i^{NC} = -m_i n_i \nu_i q^2 V_p f(X)/eB. \qquad (12)$$

The function $f(X)$ is unity for $|X|<<1$ and behaves like $\exp(-X^2)$ (plateau regime) or X^{-2} (Pfirsch-Schluter regime) (Refs.20,22). Figure 4(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, $\lambda_c \sim O(1)$. A variety of bifurcations is predicted.

The proposal of an electric bifurcation (Ref.19) was confirmed by experiments. D-III D and JFT-2M tokamaks confirmed the existence of a radial electric field (Refs.23,24). The nonlinear response of F_p to X is confirmed by the biasing experiment (Ref.25).

The gradient of the radial electric field influences the growth rate (Ref.26) and mode amplitude. Nonlinear theories on the fluid turbulence has suggested a simple and useful criterion, which is given that stabilization is expected if (Ref.27)

$$|E_r' k_\theta / B k_r| \sim \gamma_L \qquad (13)$$

where γ_L is the linear growth rate in the absence of E_r'. Recent progress has shown that the curvature of E_r has more strong influence on the stability and saturation level (Refs.28,29). The fluctuations can generates the shear flow. The quasilinear contribution of the fluctuations on the radial electric field is discussed in Eq.(3). The other non-linear processes, e.g. the inverse cascade of the fluctuations, can also generate the shear flow (Ref.30).

Dynamics

This picture of the bifurcation of the transport coefficient predicts the hysteresis between ∇n and Γ, which can generate an oscillation ('limit cycle solution'). The dynamics and the spatial structure associated with the transition has been studied (Ref.31). A model equation, continuity equation of the density and Poisson equation, can be formulated in the form of the Ginzburg-Landau equation. Figure 5 illustrates the oscillatory solution of the out-flux, and the radial profile of the effective diffusivity in H and L phases. In the phase of the good confinement, the reduction of D extends from the surface to the layer. The typical thickness is given by $\sqrt{\mu/D}\rho_p$. The result of the layer width illustrates the importance of the viscosity on the radial electric field structure.

Various types of edge localized modes (ELMs) are known in experiments (Ref.32). Some is correlated with the critical gradient of edge pressure against the ballooning mode (Ref.17), and some is not. The bifurcation theory provides a model for small and continuous ELMs.

§4. Disruptive Phenomena

The disruptive phenomena, such as the major disruption and sawtooth crash (Refs. 3,4), has also been important issue in the fusion research. We here review the effect of the anomalous transport on the MHD instability, and show that catastrophic events in disruptions is explained by the coupling between the enhanced anomalous transport due to the magnetic braiding and global mode instability.

The intrinsic feature of the major disruption is the occurrence of a sudden central temperature collapse (thermal quench), followed by a rapid change of the internal inductance (redistribution of the current), resulting in an enhanced impurity radiation which leads to the final collapse of the plasma energy and current (current quench). The essential features of the phenomena are the thermal quench and the redistribution of the internal flux. The $m=2/n=1$ mode has been been known in experiments to be important. The key task is the explanation of the sudden growth of this mode. The $m/n=1/1$ mode plays the role in the case of sawtooth. Figure 6 illustrates the evolution of the helical deformation of the plasma prior to the onset of the sawtooth crash (Ref.33). The rapid growth is seen, and at the same time, the growth rate changes abruptly. This phenomena is called the "magnetic trigger", and is one of the main problems in disruptive phenomena. The influence of the anomalous transport on the global mode stability is studied (Refs.34-36), and can explain many features including the trigger problem.

The nonlinear interaction of the main island with the toroidicity causes secondary islands to appear, which overlap near the separatrix leading to stochastization of the flux surfaces (Ref.37). This process leads to the three typical criteria in terms of the rotational transform around the main magnetic island, ω_0 (Ref.34). First, as the stochastic region emerges near the separatrix, (i) the stochastic layer thickness exceeds the current layer of the helical mode at $\omega_0>\omega_{c1}$. The rapid growth is possible as is shown below. Next, the condition (ii) $\omega_0>\omega_{c2}$ corresponds to the stochastic layer reaching the central part of the plasma, i.e., the rapid heat loss resulting in the energy quench. Then, the condition (iii) $\omega_0>\omega_{c3}$ means that the main magnetic island reaches the axis, and causes the global magnetic reconnection. Values $\omega_{c1,2,3}$ are calculated for the m=1 mode and m=2 mode, to explain the sawtooth and major disruption.

We explain the explosive growth of the mode after the condition (i) is satisfied, by taking the example from the major disruption (Ref.35). Explosive growth is possible when stochasticity appears near the separatrix. If the diffusive term is greater than the resistive term in the Ohm's equation, the growth of the m=2 mode is described by

$$\sqrt{B_n}\,\partial B_n/\partial t = C\, s^{3/2} \lambda\, \Delta' a \qquad (14)$$

Here B_n is the normalized amplitude of the m/n=2/1 mode, $C\simeq 0.14$ and Δ' is the parameter for the tearing mode stability (Ref.38). For the parameter of interest, the change of s is negligible, and s is considered to be constant. The magnetic stochasticity near the x-point enhances the current diffusivity as $\lambda= \Lambda(v_A/R)(D_M/D_{QL})B_n^2$, where D_M is the diffusion coefficient of the magnetic field lines, and D_{QL} is its quasilinear value (Ref.39). The coefficient Λ is given by $\Lambda=\pi^{3/2}(\delta/a_2)^2 v_e/v_A$ and is of the order of 10^{-4} for parameters like the JET tokamak. This coefficient is larger for smaller devices. From Eq.(14) and the form of λ, we find an explosive growth of the mode when stochastic diffusion switches on at the condition (i), which, in the limit of $D_M/D_{QL}=1$, gives

$$B_n = \frac{B_{n0}}{\{1-\sqrt{B_{n0}}\gamma_0 t\}^2}, \tag{15}$$

where $\gamma_0 \simeq Cs^{3/2}\Gamma_0\Delta' a\tau_A{}^{-1}/2$. This rapid growth occurs at the amplitude of B_n=B_{n0}. The characteristic time for the explosive growth is $\Delta t = 1/\sqrt{B_{n0}}\gamma$, which is fast and independent of the resistivity.

Stochastization of field lines, resulting from the interaction of the fundamental m/n=1/1 helical mode with toroidicity, plays an important role in sawtooth oscillations in a similar way as is shown in Fig.7 (Ref.34). The enhanced electron viscosity leads to an initial increase in the growth rate of the mode, the "magnetic trigger". The enhanced ion viscosity can ultimately lead to mode stabilization before a complete temperature redistribution or flux reconnection has occurred. The model predicts that four types of the sawtooth oscillations are possible even for a plasma with <u>monotonic</u> q(r) profile. There are two types of rearrangement of the magnetic configuration: a partial-magnetic reconnection, in which the safety factor on axis q(0) oscillates around 0.7 with $\delta q(0) \simeq 0.05$; and a full magnetic reconnection, for which q(0) oscillates between 1 and about 0.8.

In a partial reconnection the temperature flattening is rapid and can be either limited to an annulus near the q=1 rational surface, which then gradually propagates to the axis, or the temperature on axis $T_e(0)$ can rapidly decay, when the stochastic region invades the geometrical axis. Figure 8 shows the regions of these types of oscillations in the parameter space (magnetic shear and mode amplitude).

The main features of the model are compared with experimental observations. In particular, they may explain the sudden growth of the helical perturbation, the "magnetic trigger", the fast time scale of the temperature collapse, a partial temperature collapse, and the persistence of an m/n=1/1 island throughout the sawtooth cycle (Refs.4, 33).

§5. Summary

In this article, we surveyed the physics pictures of the anomalous transport from various aspects. The transport processes are essential in understanding the static plasma structure as well as the dynamic phenomena. Even the disruptive events are governed by them. The progress has been more abundant than reported here, but the example would be prototypical to illustrate the transport processes in toroidal plasmas.

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Figure Caption

Fig.1 Geometry of the toroidal plasma

Fig.2 Profiles of the density (a), toroidal velocity (c) and ion temperature. NBI heating is applied (○) and ICRF heating is added (●) in JIPP TIIU tokamak. Additional power deposition enhances the density-peaking and the rotation. (Courtesy of the JIPP TIIU group.)

Fig.3 Transition from the L-mode confinement to H-mode occurs at t≃740ms in JFT-2M tokamak (Ref.18). Change of the Hα signal indicates the reduction of loss, followed by the start of the increment of density and stored energy. Pulsative loss is also observed. (Courtesy of JFT-2M group.)

Fig.4 (a) Balance of loss cone loss Γ_i^{orbit} and electron loss Γ_e determines the radial electric field $X= e\rho_p E_r/T_i$, for various values of $\lambda=\rho_p n'/n$ (A→D). (b) The resultant flux as a function of λ. The bifurcation of the flux Γ vs gradient occurs. When Γ_e is negligible, ion viscosity-driven flux Γ_i^{NC} and Γ_i^{orbit} (solid and dashed lines, respectively) determine the radial electric field and flux, (c). Similar bifurcation nature of Γ is obtained.

Fig.5 Periodic bursts of the loss from the plasma surface is predicted for the constant flux from the core plasma, (a). The spatial profile of the diffusivity D at two occasions (arrows in (a)) are shown. $x=0$ corresponds to the surface, and $x<-2$ to the core plasma. Values of t, x, Γ_{out} and D are normalized.

Fig.6 Time development of helical deformation of the core plasma, ξ, in JET tokamak. Rapid growth abruptly appears. (Quoted from Ref.33.).

Fig.7 The sudden start of the mode-growth is explained by the destabilization through the enhanced current-diffusivity due to the magnetic braiding.

Fig.8 Schematic trajectories of the sawtooth oscillation (I-IV), and domains of stochasticity and fast growth on the s-B_n plane. The dotted line denotes the boundary (i), above which stochasticity enhances the mode growth. The lower solid line shows the condition (ii) that the stochastic region reaches near the axis. The upper solid line indicates the condition (iii) that m=1 island expands to near axis, i.e., full magnetic reconnection. Above the dashed-dotted line, the mode is stabilized by ion viscosity.

Fig. 1

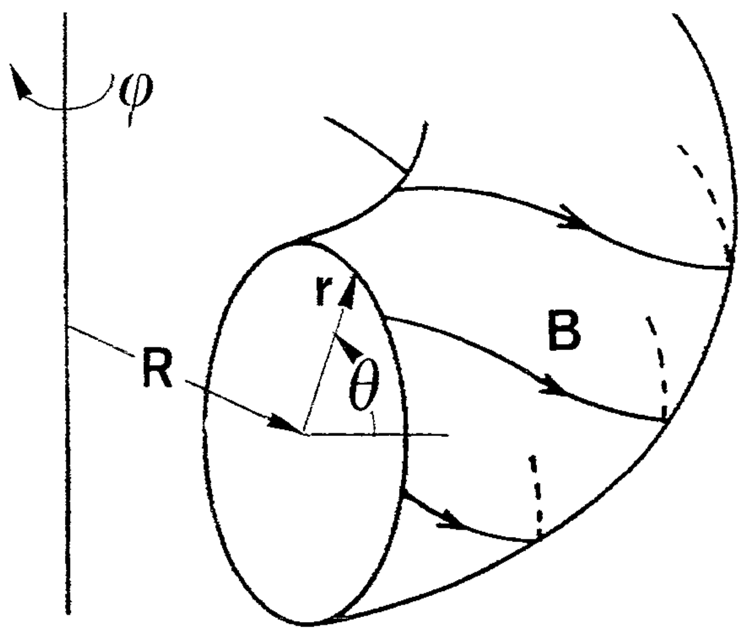
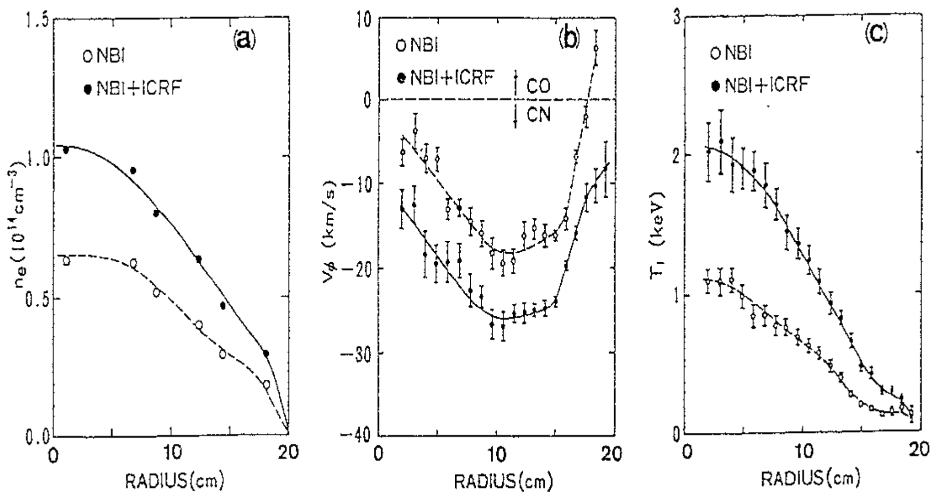


Fig.2



(a)
o NBI
• NBI+ICRF
$n_e(10^{14}cm^{-3})$
RADIUS(cm)
(b)
o NBI
• NBI+ICRF
CO
CN
V_ϕ (km/s)
RADIUS(cm)
(c)
o NBI
• NBI+ICRF
T_i (keV)
RADIUS(cm)

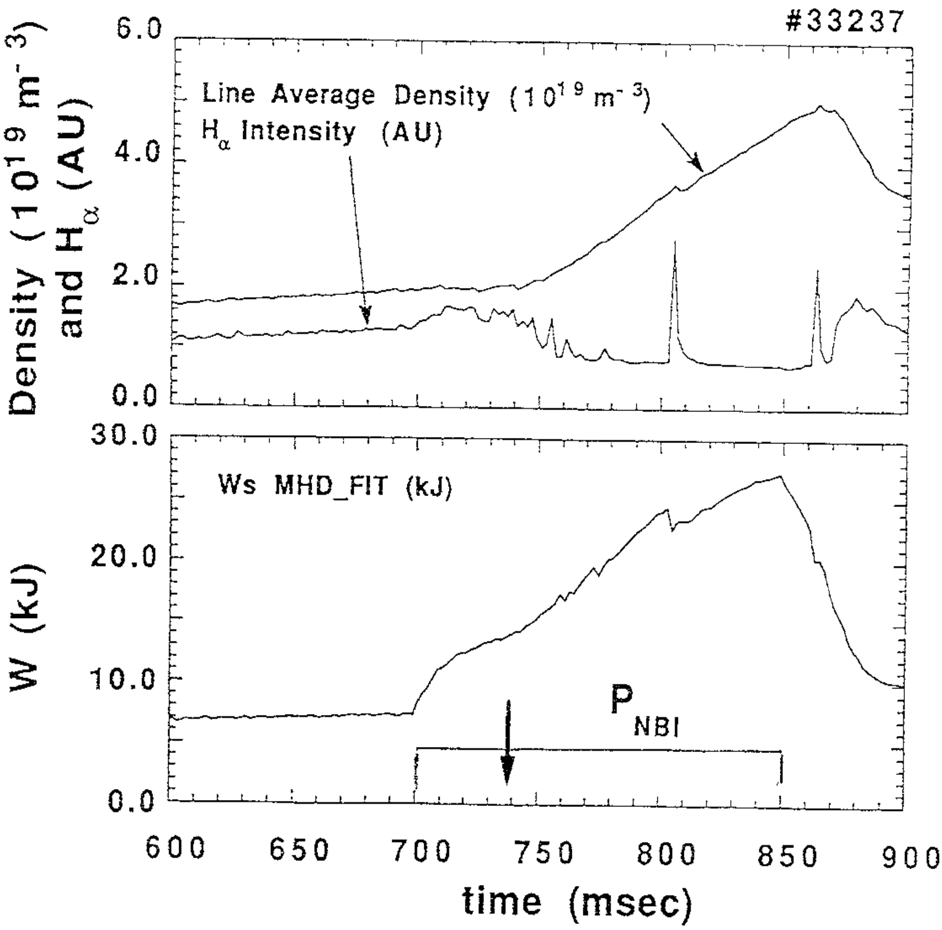

#33237
Line Average Density (10^{19} m^{-3})
H_α Intensity (AU)
Density (10^{19} m^{-3}) and H_α (AU)
6.0
4.0
2.0
0.0
30.0
Ws MHD_FIT (kJ)
20.0
W (kJ)
10.0
P_{NBI}
0.0
600
650
700
750
800
850
900
time (msec)

Fig.4

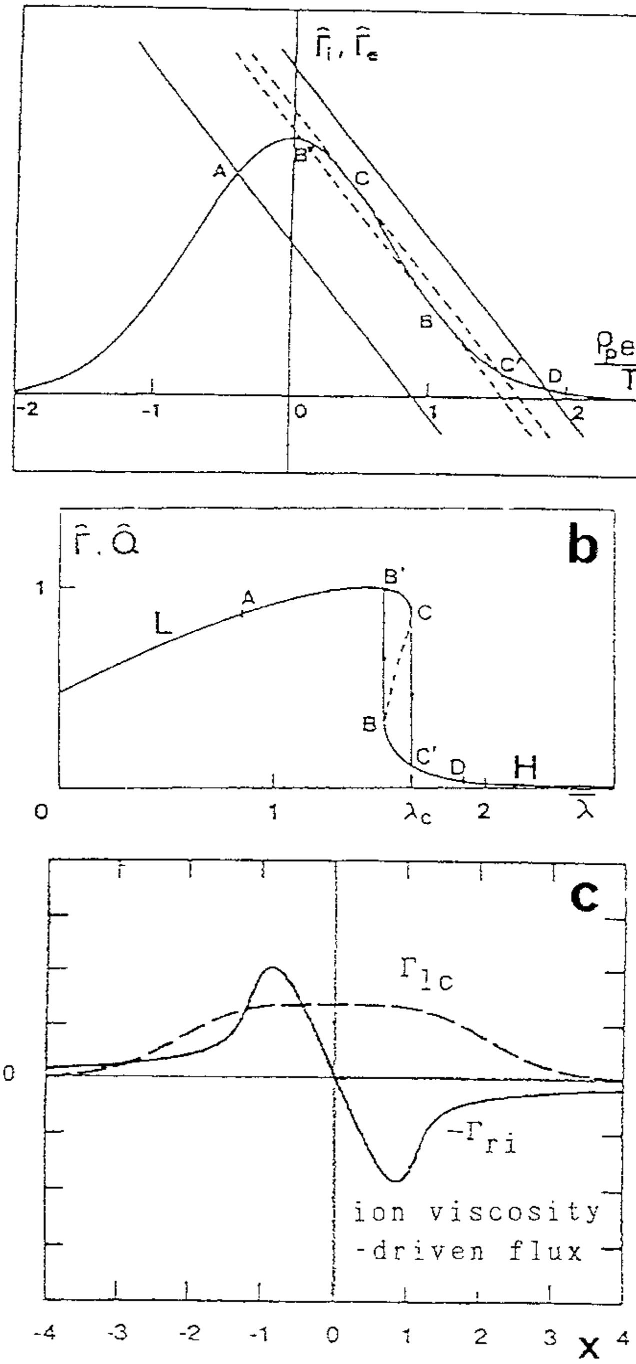

a
$\hat{\Gamma}_i, \hat{\Gamma}_e$
A
B'
C
B
C'
D
$\frac{\rho_p e E_r}{T_i}$
-2
-1
0
1
2
b
$\hat{\Gamma}, \hat{Q}$
1
A
L
B'
C
B
C'
D
H
0
1
λ_c
2
$\bar{\lambda}$
c
Γ_{lc}
0
$-\Gamma_{ri}$
ion viscosity
-driven flux
-4
-3
-2
-1
0
1
2
3
x
4

Fig. 5

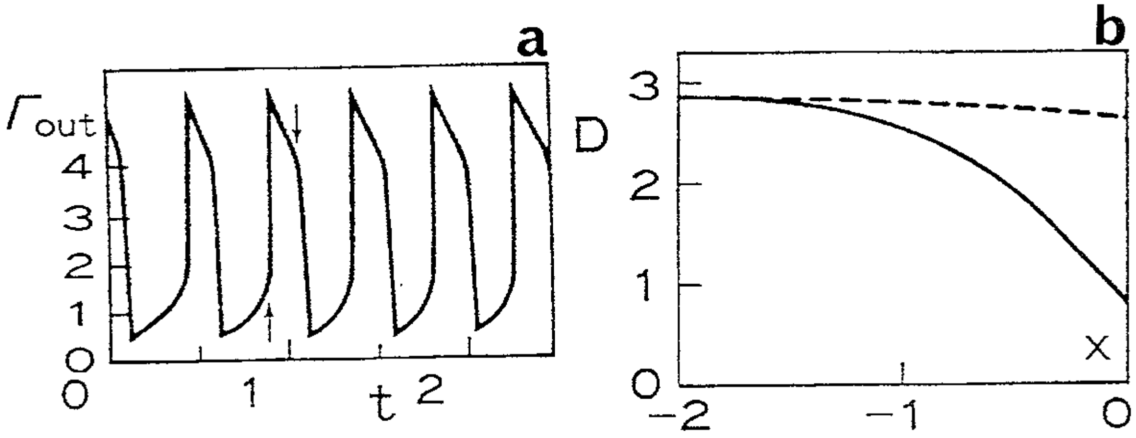


Fig.6

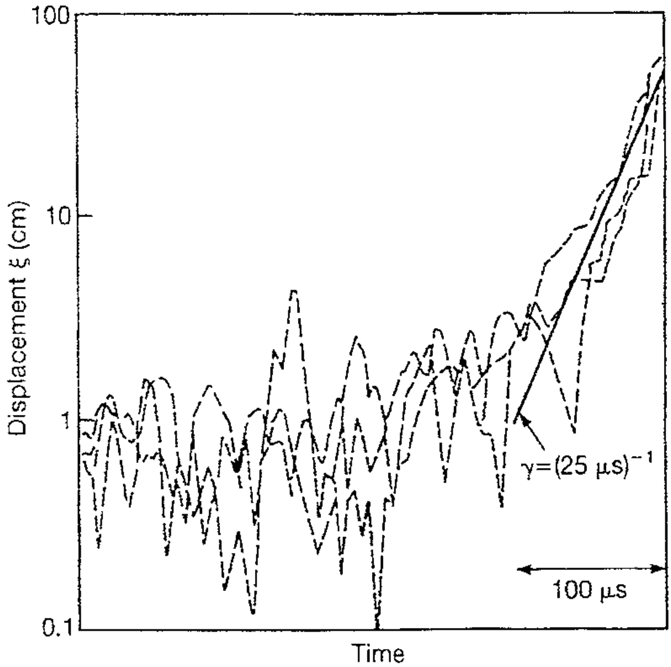


Fig.7

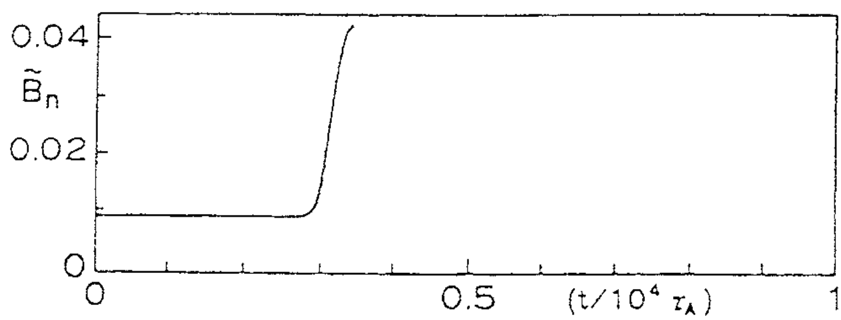
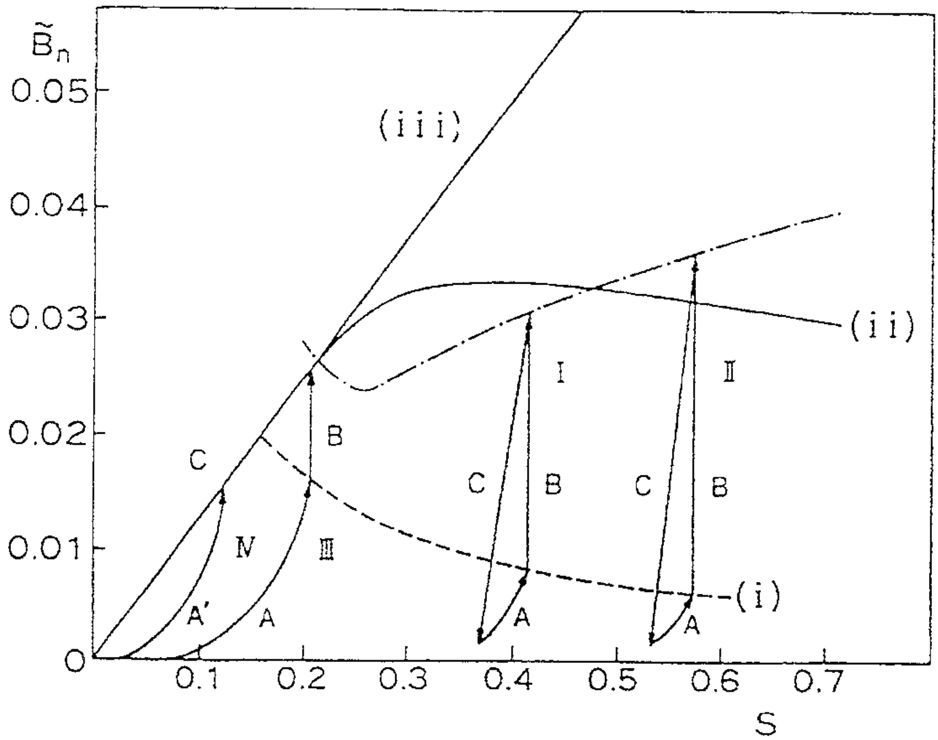


Fig. 8



$\tilde{B}_n$
0.05
0.04
0.03
0.02
0.01
0
(iii)
(ii)
(i)
C
B
IV
III
A'
A
I
II
C
B
A
C
B
A
0.1
0.2
0.3
0.4
0.5
0.6
0.7
S

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