J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 547–552

Physics Issues in Long Pulse Plasma Confinement

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(Received: 18 January 2000 / Accepted: 21 March 2000)

Abstract

Physics in the steady-state or long time discharge are illustrated from the view point of generic toroidal plasmas. Issues include physics process with very long time scale, dynamical phenomena of various time scales, transition nature under very slow temporal variations of parameters, statistical occurrence of transition and life time and identification of minimum circulating power. Nonlinear dependencies of transport properties of density, temperature, current, electric field and poloidal magnetic field cause self-organized dynamics. A picture of stationary oscillatory states is presented from a unified picture of nonlinear limit cycle dynamics. It is emphasized that the long time asymptotics are determined by the structure formation mechanisms. The sustainment needs a circulating power, and the circulating power in steady state plasma is also discussed.

Keywords:

stationary state, self-generated oscillations, bifurcation, density limit oscillation, thermo-electric oscillation, statistical excitation, circulating power

1. Introduction

Recently attentions are attracted to the study of steady-state sustainment of confined plasmas. This is motivated by the progress in experiments which aim the physics of steady state plasmas (see, e.g., [1]) or by the design of fusion experimental reactor like ITER [2]. The circulating power for the sustainment must be as low as possible if one considers the economy as well as dependability of the reactor system. At the same time, investigations of steady state plasma at high plasma temperature provide unique opportunity to explore the physics of confined plasmas. In "steady-state", plasma parameters evolve into self-regulated dynamical states, often being associated with self-organized oscillations [3].

In this survey, physics advancement are discussed from the generic view point of theory and modelling of high temperature toroidal plasmas. Key features of steady state plasmas might be summarized as: (1) Study of the physics process with very long time scale is possible; (2) Dynamical phenomena, which are generated by the combination of processes with various time scales, shall be investigated; (3) Very slow temporal variations of parameters illustrate precisely the transition nature of confined plasmas; (4) Transition events can be observed in a very long discharge, by which the concepts of statistical occurrence and life time are constructed; and (5) Identification of minimum circulating power would be pursued. Physics processes of these directions of research are illustrated, and the theory and modelling are discussed, putting an emphasis on the understanding of the improved confinement.

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2. Dynamics in Stationary-State Plasma

2.1 Dynamical models

Simple set of transport equations is taken in order to study the dynamics of the plasma. As parameters that characterize the plasma state, the electron density n, impurity density n_I, temperature T, radial electric field E_r, and toroidal current J_ϕ are chosen. The dynamical model consists of the particle balance equation,

$$\frac{\mathrm{d}}{\mathrm{d}t} n = -\nabla \Gamma_r + S_p \tag{1}$$

the equation of the momentum or the radial electric field

$$\frac{\mathrm{d}}{\mathrm{d}t} E_r = \nabla_\perp \mu_\perp \nabla_\perp E_r - \hat{J}_r \tag{2}$$

equation for temperature

$$\frac{\mathrm{d}}{\mathrm{d}t} nT = -\nabla q_r - \frac{P_{rad}}{3V} + \frac{P_{abs}}{3V} \tag{3}$$

Ohm's law

$$E_\varphi = \eta_{NC} J_\varphi - \eta_{NC} J_{BS} \tag{4}$$

and the particle balance equation for impurity,

$$\frac{\mathrm{d}}{\mathrm{d}t} n_I = -\nabla \Gamma_I + S_I \, . \tag{5}$$

Transport relations between plasma parameters and fluxes Γ_r, Γ_I, q_r, and $\mu_\perp \nabla_\perp E_r$ are shown in e.g., [3]. Particle sources S_p and S_I, radial current $\hat{J}_r$, energy input source P_{abs}, radiation loss P_{rad} and Bootstrap current J_{BS} play the role of source terms in this dynamical system.

2.2 Self-sustained dynamics and long-time asymptotics

The system of eqs. (1)–(5) has a solution which is constant in time. Nevertheless, a variety of dynamical solutions are allowed. A perspective of the long-time asymptotics, which is the key for the fusion reactor, is obtained only after the dynamical nature will be fully understood. Here we discuss the self-organized dynamics which are included in this system under the external constraints which are constant in time.

2.2.1 H-mode and related problems

Improved confinement state is considered to be realized by the bifurcation of radial electric field being associated with the reduction of anomalous transport owing to the inhomogeneity of E_r [4]. This property of radial electric field depends strongly on the nonlinear dependence of source radial current on electric field, $\hat{J}_r[E_r]$. (See also review of [5].) Stationary solution of Eq. (2) allows multiple steady-state solutions (constant in time). If coupled with the evolution of the density and/or temperature, there could arise the self-regulated oscillation [6]. (See Fig. 1.) A limit cycle oscillation has been obtained, and is attributed to the dithering ELMs [6,7]. Multiple nonlinearlities could drive compound dithers [8].

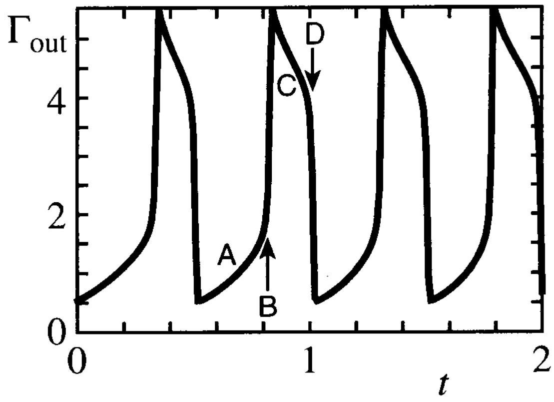

Fig. 1 Self-generated oscillation of the outflux at edge for constant supply form core [Quoted from [6]).

Problems in the long-time plasma include the control of particle source in realizing the improved confinement. It is well known that the control of particle source was essential in exploring various improved confinement modes [9]. For instance, role of neutral particle has been theoretically investigated in connection of the H-mode [5], and an analysis has been extended to study the impact of wall material on H-mode performance [10]. These properties could change in a long-time discharge. If one writes the particle source as $S_p = S_p^{ext}/(1 - \hat{R})$ where S_p^{ext} is the external supply and $\hat{R}$ is the recycling coefficient, the recycling coefficient is not constant in time. It is dependent on the plasma flux and diffusion process in the material. Low frequency dynamics is predicted by the dynamical evolution of plasma parameters and $\hat{R}$. The importance must be noticed for the wall material, for which we shall have less freedom in the future burning experiments. Because the wall material has considerable impact for the improvement factor of the confinement [11], the limitation in the choice will have to be compensated by the external control of the plasma profiles, which is discussed in the later part of this article.

2.2.2 Electric oscillation in helical system

In helical systems, the neoclassical ripple transport could play a dominant role in the term $\hat{J}_r[E_r]$ [12]. Bifurcation of electric field and transport has been studied. The electric field interface, across which radial domains with different electric field polarity touch, has

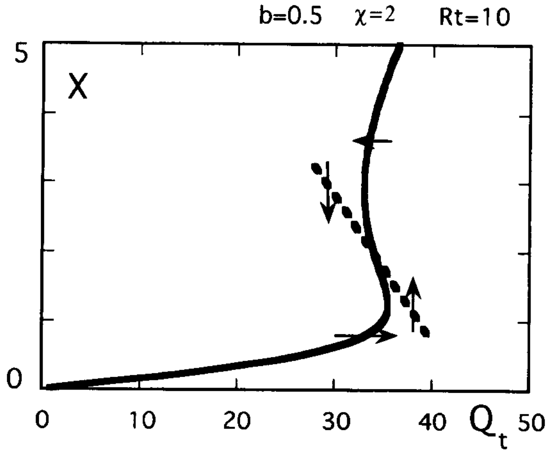

Fig. 2 Radial electric field X as a function of the heat flux is shown by the solid line. Self-generated oscillation is possible. Solid and dashed lines indicate $\partial X/\partial t = 0$ and $\partial Q_r/\partial t = 0$, respectively.

been predicted as a possibility for the internal transport barrier [3]. This has been confirmed by CHS [13]. Application to LHD has been given in [14].

The bifurcation and dynamics is studied. Figure 2 (solid line) illustrates the normalized radial electric field $X = eaE_rT_e^{-1}$ as a function of the normalized radial energy flux $Q_t \propto q_{e,tot}T_e^{-4.5}$ [15]. At critical energy flux, the electric field jumps to a higher branch in which the neoclassical energy diffusion is much smaller. This is a stationary solution of Eqs. (2) and (3). Dashed line in Fig. 2 shows $dQ_t/dt = 0$. As a result, if the energy flux is chosen as Fig. 2, there arises a limit cycle oscillation of the electric field and temperature.

2.2.3 Thermo-electric oscillation

Under the constant external heating, the absorbed power depends on the plasma parameter and electromagnetic field. This dependence causes another self-organized dynamics. Example is seen in helical plasmas. The heating efficiency is influenced by the loss cone. If there is a resonance (i.e., the potential difference $\phi(a) - \phi(0)$ has a same sign for the charge sign) [16], energetic particles are lost when the energy is decelerated (in case of NBI) to $W_{loss} = e\{\phi(a) - \phi(0)\}/\varepsilon_h(a)$ where $\varepsilon_h(a)$ is a helical ripple at surface. The heating efficiency is estimated as $(W_{in} - W_{loss})/W_{in}$ and the absorbed power is estimated as $P_{abs} = (1 - W_{loss}/W_{in})P_{dep}$ where W_{in} is the injection energy and P_{dep} is the deposited power.

This dependence of the absorption power on the radial electric field introduces a new dynamics. When the plasma temperature increases, usually the electric field becomes stronger as well. Then the absorption power could be reduced by this relation, so as to decrease the temperature. This type of oscillation is called thermo-electric oscillation [17].

2.2.4 Oscillatory improved confinement

If one observes the long time behaviour of the current profile change, oscillatory improved confinement is predicted to occur in high beta plasmas. Coupling between the transport coefficient and plasma profiles drives the nonlinear oscillation of confinement time [18]. In the system with magnetic well, dissipative ballooning mode turbulence has been analyzed. The thermal conductivity χ is given as an increasing function of the pressure gradient, denoting the degradation of confinement at high heating power, but becomes smaller when the magnetic shear is weak or negative. This is pointed out as a cause of improved confinement of high-β_p mode and negative shear mode [19]. The coupling of Eqs. (3) and (4) describe the formation and dynamics. The large pressure gradient drives Bootstrap current so as to flatten the current profile. The flattened current reduces transport so as to increase the pressure gradient. This nonlinear link allows the transport barrier formation. The diffusion of the magnetic flux leads the change of shape of magnetic shear, so that the transport barrier structure becomes oscillatory.

2.2.5 Density limit oscillation

In impure plasmas, the radiation loss plays the important role in the long time evolution of the confined plasma. The dependence of the radiation loss on the temperature and density, $P_{rad} = n_e n_I \langle L_z(T)\rangle V$ with $\langle L_z(T)\rangle = \xi T^{-\gamma}$, is known to cause the radiation instability, which would bound the operational density of toroidal plasmas. (See, e.g., [20].) Combinations of Eqs. (1), (3) and (5) also predicts the self-organized dynamics near density limit, which prevents the radiation collapse at the density limit. When radiation instability collapse continues and the temperature becomes lower than the critical value, the inhomogeneities of temperature and potential on the magnetic surface become unstable. By the growth of the symmetry-breaking perturbations, the rapid loss takes place. The details is discussed in [21]. The critical condition for this instability is given in terms of the density and temperature as

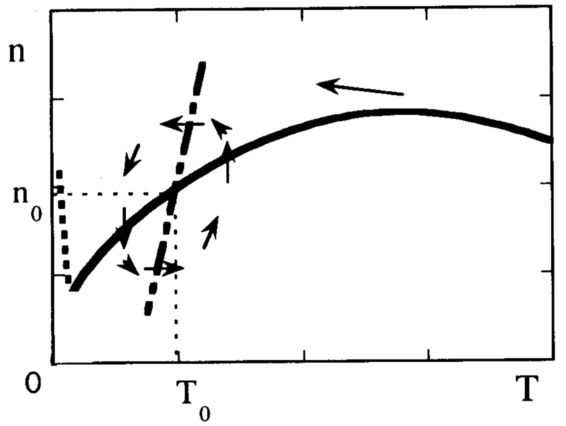

Fig. 3 Flow diagram. Solid lines and thick dot-dashed lines represent the stationary solution of eqs. (3) and (1), respectively. Time derivative (dT/dt, dn/dt) is shown by the arrow.

$$T n^{-y} \leq \zeta \equiv \left(\frac{q^2 R^2}{3\chi_0} \frac{n_I}{n_e} \xi \right)^{1/(\gamma+3.5)} \tag{6}$$

where $y = (\gamma + 3.5)$ and the parallel transport coefficient is assumed to have a form $\chi_{\parallel} = \chi_0 n^{-1} T^{2.5}$. When this instability occurs, the rapid plasma loss happens. By the onset of the reduction of density, the radiation collapse stops to continue, and the high temperature plasma can be recovered. This process repeats itself as is shown in Fig. 3. This self-generated oscillation of density and radiation loss is a model of density limit oscillation in W7-AS stellarator [22].

3. Concept of Statistical Excitation

An important issue of the plasma turbulence is the phenomena related to its subcritical excitation [3]. The importance has been known in experiments. Very abrupt symmetry-breaking perturbations, which include both microscopic turbulence and global perturbations, have often been observed (known as 'trigger event') and the temporal change of the growth rate of perturbation cannot be described from the slow variation of the global parameters that govern the linear growth rates [23]. The experimental study on the very long-time plasmas allows a detailed study of the evolution in trigger phenomena. In addition, the statistical occurrence of transition was predicted [24,25]. The deductive theory is also addressed to predict the statistical property of the transition in turbulence. The generalization of Arrhenius law [26] has been derived in the new statistical theory of far-nonequilibrium plasmas [27]. There, the characteristic dependence on the gradient is explicitly obtained, and the power law in the transition probability has been obtained.

The power law distribution with respect to the distance of plasma parameter from the operational boundary is calculated [24]. By this theoretical analysis, a concept of life time is introduced [25]. A statistical view, not the deterministic view, is explained. This is an area where varieties of progress of research are expected in the future.

An illustration is made how the very long time discharge allows a detailed investigation on the transition physics in confined plasmas. Small amount of the change of plasma parameters could trigger the transition (like electric field bifurcation). A gradual change of plasma parameters are used to investigate the transition features. Examples are taken from the problems of catastrophic events and transport barriers. These aspects of the steady-state plasmas are stimulating and provide areas of future progress in plasma physics for confined plasmas.

4. Minimum Circulating Power

The sensitivity of the confinement improvement or stability at high-beta to the profile casts a problem in the future perspectives for the stationary plasmas. First, in the stationary plasmas, the profiles will be less dependent on the initial condition of the plasma formation. Second, the stationary plasma will be subject to the stronger influence of the surrounding materials. For instance, the 'resistive wall' mode is an important issue under the circumstances of the wall with the finite *L/R* time [28]. Also important will be the wall material, for which we shall have less freedom in the future burning experiments. The profile control becomes more and more important for the stable and steady-state tokamaks. In particular, the rotation drive is one of the most important issues, because it is strongly related to the MHD stability and improved confinement.

We here discuss the circulating power and efficiency of the rotation drive in tokamaks. One important element of the circulating power in tokamaks is the current drive power, which might be reduced by the Bootstrap current. The ratio of the Bootstrap current, I_{BS}, to the total plasma current, I_p, is evaluated as $I_{BS}/I_p = 0.7\sqrt{a/R}\,\beta_p$ where a and R are minor and major radii, respectively, and β_p is the plasma pressure normalized to the poloidal magnetic field pressure [29]. The current-drive power reduces as β_p reaches the value $1.4\sqrt{R/a}$.

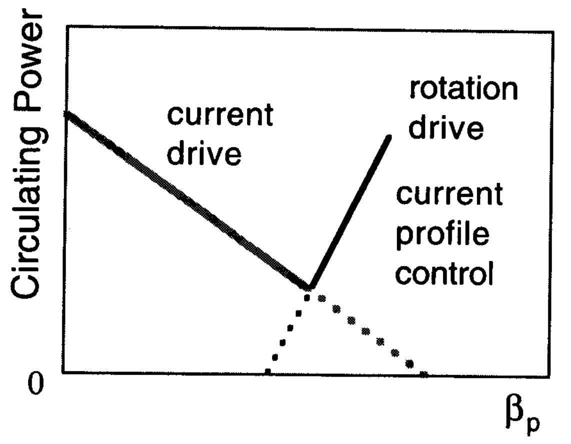

Fig. 4 Schematic illustration of the necessary circulating power for the current drive, current profile control and rotation drive as a function of β_p.

However, as is schematically illustrated in Fig. 4, circulating power does not vanish, and is increased when β_p becomes high. This is for the stability of MHD activities like nonlinear tearing mode (e.g., neoclassical tearing mode) or resistive wall mode, which becomes unstable when β_p is high. The competing demands determine the minimum circulating power for the steady-state tokamaks.

The necessary momentum injection, M, to sustain the plasma rotation is evaluated as $M \cong \mu_\perp a^{-2} m_i n_i (v_\varphi - v_{\varphi *})V$ where m_i is the ion mass, n_i is the ion density, v_φ is the toroidal velocity. The off-set $v_{\varphi *}$ is the spontaneous plasma rotation in the absence of the external torque, which is discussed in [30]. We study the case where the rotation is directly sustained by the external momentum injection (i.e., $v_{\varphi *} = 0$). The necessary power P_b is illustrated by comparing it to the heating power P_{heat}, $P_{heat} = 3nTV\tau_E^{-1}$, where we choose the condition $T_e = T_i = T$ and $n_e = n_i = n$ for the simplicity. The energy confinement time is expressed in terms of the thermal conductivity χ as $\tau_E = a^2/\chi$. We have the ratio in the absence of the spontaneous rotation as

$$\frac{P_b}{P_{heat}} = \frac{\sqrt{6}}{3}\frac{\mu_\perp}{\chi}\sqrt{\frac{W_{in}}{T\beta}}\frac{v_\varphi}{v_A} \tag{7}$$

where we assume $m_b = m_i$. For a typical parameters of ignited plasmas, $T = 10$ keV, $\beta = 0.1$, $W_{in} = 1$ MeV, the requirement of the rotation velocity of $v_\varphi/v_A = 0.04$ [31] implies the circulating power of the order $P_b/P_{heat} \cong \mu_\perp/\chi$. This ratio is the inverse of the Prandtl number, and is in the range of 1/3 to 1/2 for the anomalous transport [32], i.e., $P_b/P_{heat} \cong 1/3 \sim 1/2$. This level of the circulating power is not tolerable for the steady state tokamaks. The direct drive by the external torque is found to be not efficient enough. This result shows that the role of the spontaneous rotation is essential. Rotation drive by the α-particles in the ignited plasma is also investigated. These studies are given in [30].

5. Summary

In this article, we discussed various physics issues in the steady-state or long time discharge. Key features of steady-state plasmas were illustrated from the view point of generic toroidal plasmas as: (1) study of the physics process with very long time scale; (2) dynamical phenomena, which are generated by the combination of processes with various time scales; (3) transition nature which is investigated in very slow temporal variations of parameters; (4) concepts of statistical occurrence and life time; and (5) Identification of minimum circulating power. Physics processes and the directions of research are illustrated. Nonlinear dependencies of transport properties of density, temperature, current, electric field and poloidal magnetic field cause self-organized dynamics. A picture of stationary oscillatory states is presented from a unified picture of nonlinear limit cycle dynamics.

It is emphasized that the long time asymptotics are determined by the structure formation mechanisms. Many features of the improved confinement state, which have been observed, are related with the initial condition of the plasma formation. Asymptotic behaviour of the improved confinement in the long time discharge might be different from those known empirically so far. The sustainment needs a circulating power. The minimization of the circulating power, based on the understanding of the nonlinear transport and turbulence, is a key for the future research of the magnetic confinement.

Acknowledgements

Discussion with members of Theory and Data Analysis Division, Dr. K. Ida and Dr. A. Fujisawa, Prof. A. Yoshizawa and Dr. L. Giannone is acknowledged. This work is partly supported by the Grant-in-Aid for Scientific Research of Ministry of Education, Science, Sports and Culture Japan. Also acknowledged are the collaboration programme of National Institute for Fusion Science and the collaboration programme of Research Institute for Applied Mechanics (Advanced Fusion Research Center) of Kyushu University. Part of this work is completed during two of the authors' (KI and SII) stay at Max-Planck-Institut für Plasmaphysik (IPP), which is supported by the Research-Award Programme of Alexander von Humboldt-Stiftung (AvH).

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