ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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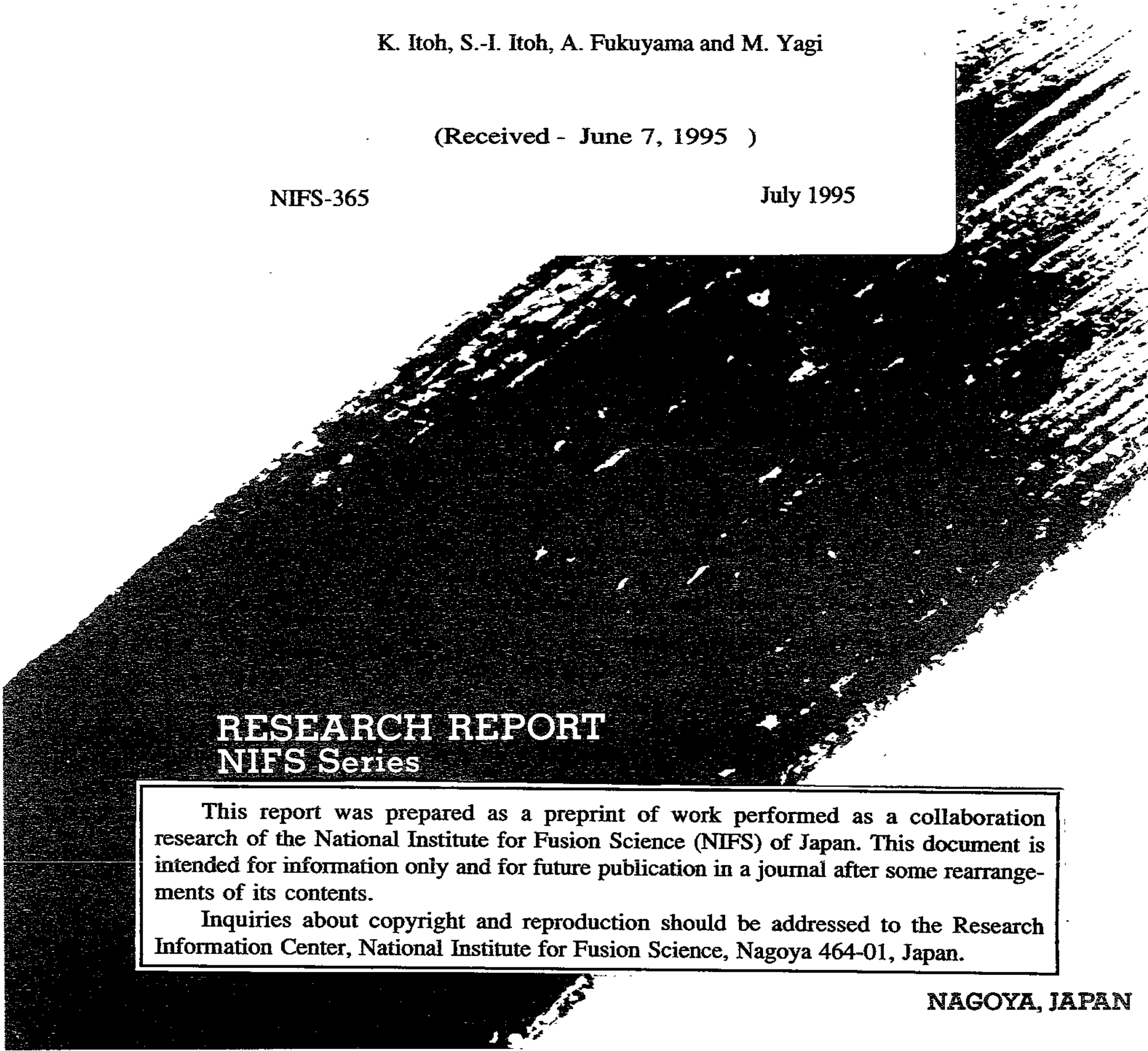
(Received - June 7, 1995)

NIFS-365 July 1995



RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

On the Minimum Circulating Power of Steady State Tokamaks

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Abstract

Circulating power for the sustenance and profile control of the steady state tokamak plasmas is discussed. The simultaneous fulfillment of the MHD stability at high beta value, the improved confinement and the stationary equilibrium requires the rotation drive as well as the current drive. In addition to the current drive efficiency, the efficiency for the rotation drive is investigated. The direct rotation drive by the external torque, such as the case of beam injection, is not efficient enough. The mechanism and the magnitude of the spontaneous plasma rotation are studied.

Keywords: Plasma Rotation, Viscosity, Circulating Power, Steady State Plasma, Current Drive, Rotation Drive, MHD Instability, Improved Confinement, Ignition

1. Introduction

Recently, the study on the improved confinement of tokamak plasmas has revealed the importance of the profiles of the density, current and rotation. The stability against ideal magnetohydrodynamic (MHD) instability requires a careful choice of the current profile and the pressure profile. The simultaneous fulfillment of the improved confinement and stability is necessary not only for the realization of the ignited plasma but also for the enhancement of the efficiency. The improvement in the confinement or in the MHD stability depends on the control of plasma profiles. The experimental variety in the plasma profile made flourishing of the various improved confinement modes [1].

This sensitivity 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. The variety in the profiles, without external efforts to control, will be reduced. In other words, the optimization of confinement or the stability through the profile control will require the circulating power to control the profile in the steady state. 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 [2]. Also important will be 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 [3], the limitation in the choice will have to be compensated by the external control of the plasma profiles. The efficiency of the rotation drive is as important as the current drive efficiency for the steady state advanced tokamaks.

In this article, we study the efficiency of the rotation drive in tokamaks. The required power in order to stabilize the MHD mode is discussed. The direct drive by the external torque is found to be not efficient enough. The role of the spontaneous rotation is stressed. Rotation drive by the α-particles in the ignited plasma is investigated. The purification of the plasma by the rotation is also discussed.

2. Profile Control and Rotation Drive

Table 1 shows the profile control in the density, velocity, current, pressure and impurity. The first column shows the necessities of the profile control. The second column indicates the damping (dissipation) mechanisms, which cause the decay of the profile of each component. The third column lists the processes that appears as a spontaneous mechanism to realize the peaking (or the change, at least) of the profiles. The fourth column is for the external method for the control. In the last column, the events which lead to the transient/dynamic change of profiles are listed. We study in this article a stationary state, although these transient events could have important impact on the profile control efficiency.

This table illustrates the importance of the combination of the current profile and rotation profile. One example is seen in the evaluation of the minimum circulating power of the plasma with a high-fraction of the Bootstrap current [4]. The ratio of the Bootstrap current, I_{BS}, to the total plasma current, I_p, is evaluated as

$$\frac{I_{BS}}{I_p} = 0.7\sqrt{\frac{a}{R}}\,\beta_p$$

where a and R are minor and major radii, respectively, and β_p is the plasma pressure normalized to the poloidal magnetic field pressure. The rest of the Bootstrap current, $I_p - I_{BS}$, must be driven by a non-inductive method. This result indicates that the circulating power to sustain the total current becomes very small, when β_p reaches the value $1.4\sqrt{R/a}$. (At this condition $\beta_p = 1.4\sqrt{R/a}$, the necessary power for the non-inductive current drive is the one for the seed current at the axis [5]. This power could be annihilated if one counts for the role of the current-diffusion [6]. However, the question of the small seed current is out of the scope in this article.) The circulating power could not always be lowered to this value. This is because that the internal inductance l_i in such a plasma is low. The MHD beta limit is usually known to increase with l_i, i.e., $\beta_{limit} \propto \ell_i$ [7]. The energy confinement time is in proportion to l_i for the L-mode plasma [8]. Owing to these reasons, the internal inductance could be bounded above a certain lower limit, which in turn determines the allowable contribution of the Bootstrap current to the total plasma current. Figure 1 schematically illustrates this situation. Above the beta value of the minimum current drive power, the anti-current drive in the midway (say, $r \approx a/2$) and the current drive in the center are required, in order to keep the internal inductance constant against the influence of the Bootstrap current. The MHD stability could be improved by the rotation. By the help of the rotation, the minimum current drive power could be lowered. The rotation drive efficiency is the key.

3. Rotation Drive Efficiency

The rotation drive efficiency η_{rot} is defined as

$$\eta_{rot} = \frac{\langle v \rangle}{P_{rot}} \tag{1}$$

where <v> is the average velocity of the plasma rotation and P_{rot} is the necessary power from the external supply. Both the poloidal and toroidal rotations are available, hence the efficiency could be defined for both rotations. The local efficiency could also be defined, but a simplified argument is developed here. The efficiency is determined by three issues:

$$\frac{v}{P_{rot}} \propto \frac{\text{velocity}}{(\text{dissipation}) - (\text{spontaneous drive})} \tag{2}$$

The [velocity] in the numerator is required by various reasons; the MHD stability, the improved confinement, the thermal stability or the purification of the plasma. The [dissipation] in the denominator is due to the viscosity or the drag by neutrals. The [spontaneous drive] in the denominator comes from the off-diagonal elements in the transport matrix. Theoretical studies has been developed [9] and experimental study has also investigated the spontaneous plasma rotation [10]. The neoclassical as well as the anomalous transport plays a role, and the alpha particles also work for it.

In the core plasma, the bulk viscosity for the poloidal rotation is usually stronger than the shear viscosity for the toroidal rotation. We therefore study the case of the toroidal rotation.

The necessary momentum injection, M, to sustain the plasma rotation is evaluated as

$$M \cong \frac{\mu_\perp}{a^2} m_i n_i \left(v_\phi - v_{\phi *}\right) V_p \tag{3}$$

where $\mu_\perp$ is the shear viscosity with the estimation $\left|\mu_\perp \nabla_\perp^2\right| \simeq \mu_\perp a^{-2}$, m_i is the ion mass, n_i is the ion density, v_ϕ is the toroidal velocity, and V_p is the plasma volume. The off-set $v_{\phi *}$ is the spontaneous plasma rotation in the absence of the external torque, which will be discussed in later.

If the necessary torque is supplied by the beam injection, the momentum supply M and the beam power P_b has the relation $M \le 2P_b/v_b$, where the equality holds for the parallel injection (v_b being the velocity of the beam). The lower bound for the required power is given as

$$P_b = \frac{\mu_\perp}{a^2} \frac{v_b}{v_{th}} n_i T_i V_p \frac{\left(v_\phi - v_{\phi *}\right)}{v_{th}} \tag{4}$$

Substituting Eq.(4) into Eq.(2), the upper bound for the rotation drive efficiency is written as

$$\eta_{rot} = \frac{a^2}{\mu_\perp} \frac{2}{n_i m_i V_p} \frac{1}{v_b} \frac{v_\phi}{v_\phi - v_{\phi *}} \tag{5}$$

The rotation drive efficiency is inversely proportional to v_b, if $v_{\phi *}/v_\phi$ is fixed. This result indicates the importance of the spontaneous drive for the rotation control. When the momentum is injected not by the beams (e.g., by use of rf waves), a proper equation for the ratio of M to the power should be used.

In the following, we discuss the efficiency and the necessary power for various cases.

3.1 Improved Confinement and High-n MHD Instability

High-n ballooning mode is a candidate to determine the beta limit in tokamaks (n: toroidal mode number). For such a mode, the local shear of the rotation velocity is effective for stabilization. It is shown that the beta limit against this mode is considerably improved if the condition

$$\frac{s_v}{s} \geq \frac{1}{3} \tag{6}$$

is satisfied (see, e.g., [11]). In this expression, $s_v = (Rr/v_{th}) d/dr(E_r q/rB)$, r: minor radius, v_{th}: thermal velocity of main ions, E_r: radial electric field, B: main magnetic field, q: safety factor and s is the shear parameter, rq'/q. This condition Eq.(6) could be rewritten in terms of the parameter $\omega_E = E_r' \tau_{Ap}/sB$ (τ_{Ap}: qR/v_A, v_A: Alfven velocity) as

$$\omega_E \geq \frac{1}{3} \tag{7}$$

The parameter ω_E is introduced to investigate the reduction of the thermal conductivity due to the inhomogeneous radial electric field as [12]

$$\chi_H = \frac{\chi_L}{1 + h(\alpha, s)\omega_E^2} \tag{8}$$

where $\alpha = -q^2R\beta'$, and the suffix H and L denote the H-mode and L-mode, respectively. The explicit form of $h(\alpha,s)$ was given in [12], and is not reproduced here. The dependence was found $h \propto 1/\alpha$ in the small α-limit and $h \propto \alpha$ in the large α-limit. For the typical parameters, $\alpha = 0.3$, $s = 0.5$ and $q = 3$, $h \approx 24$ holds. In other words, χ_H is reduced by the factor 3 in comparison with χ_L if $\omega_E = 0.3$. We find that the linear ideal MHD stability condition (high-n mode) is relaxed if the improved confinement due to the radial electric field inhomogeneity is realized. This indicates that no additional circulation power for this MHD stability is necessary if the improved confinement is realized by the spontaneous mechanisms.

3.2 External Drive of Rotation and Resistive Wall Mode

The necessary power is not the same if one considers the suppression of the resistive wall mode at high beta value. This mode is the global mode. The local inhomogeneity of the velocity is not enough, but the plasma column must rotate with a high velocity such as a few hundredths of v_A. We study the case where the rotation is directly sustained by the external momentum injection. The necessary power and the efficiency for this direct method are calculated from Eqs. (4) and (5). The efficiency is illustrated by comparing the power P_b to the heating power P_{heat},

$$P_{heat} = 3nTV_p\tau_E^{-1}, \tag{9}$$

where we choose the condition $T_e = T_i = T$ and $n_i = n_e = n$ for the simplicity. The energy confinement time is expressed in terms of the thermal conductivity χ as $\tau_E = a^2/\chi$. The normalization of v_ϕ to v_A is made, $v_\phi/v_{th} = \sqrt{6/\beta}\left(v_\phi/v_A\right)$. Using these relations, we have the ratio P_b/P_{heat} in the absence of the spontaneous rotation as

$$\frac{P_b}{P_{heat}} = \frac{\sqrt{6}}{3}\frac{\mu_\perp}{\chi}\sqrt{\frac{E_b}{T\beta}}\frac{v_\phi}{v_A} \tag{10}$$

where E_b is the beam energy, and we assume $m_b = m_i$. We see that, the higher the beam energy becomes, the larger the circulating power is.

For a typical parameters of ignited plasmas, T = 10keV, $\beta = 0.1$, $E_b = 1\mathrm{MeV}$, the requirement of the rotation velocity of $v_\phi/v_A = 0.04$ [13] implies the circulating power of the order

$$\frac{P_b}{P_{heat}} \cong \frac{\mu_\perp}{\chi} \tag{11}$$

The right hand side of this equation is the inverse of the Prandtl number, and is in the range of 1/3 to 1/2 for the anomalous transport [14]. This ratio varies only weakly both in the L-mode and H-mode.

$$\frac{P_b}{P_{heat}} \cong \frac{1}{3} \sim \frac{1}{2} \tag{12}$$

This level of the circulating power is not tolerable for the steady state tokamaks.

3.3 Spontaneous Drive

The analysis in section 3.2 indicates the importance of the spontaneous rotation drive in the confined plasmas. In the framework of the self-sustained turbulence, the off-diagonal element of the transport matrix is also evaluated with the diagonal elements. By employing the reduced set of equations, the radial flux of the momentum $P_{\perp r}$ is expressed as [9]

$$\frac{P_{\perp r}}{m_i n_i v_{Ap}} = M_{11} \nabla \left(\frac{1}{v_{Ap}} \frac{\nabla \phi}{B} \right) - M_{12} \nabla \left(\frac{qR}{a} \beta \right) \tag{13}$$

where M_{ij} is the (i, j) element of the transport matrix, and M_{11} is related to the shear viscosity $\mu_\perp$. The second term in the right hand side is the off-diagonal transport: in this case, the drive of the rotation by the pressure gradient.

In a stationary state (i.e., there is no external momentum source), the potential difference, $\Delta\phi = \phi(a) - \phi(0)$, (and the $E \times B$ velocity as well) is given as

$$\frac{1}{v_A}\frac{\Delta\phi}{a\,B} \approx \frac{M_{12}}{M_{11}}\beta \tag{14}$$

where the estimation $\nabla \approx 1/a$ is used. This equation is rewritten as

$$\frac{e\Delta\phi}{T} \approx \frac{M_{12}}{M_{11}}\frac{6a\omega_p}{c}\sqrt{\frac{m_e}{m_i}} \tag{15}$$

The off-diagonal element is estimated by use of the theory of the self-sustained turbulence as [15]

$$\frac{M_{12}}{M_{11}} \approx \frac{F^2(\alpha,s)}{4q}\sqrt{\frac{m_i}{m_e}}\frac{c}{a\omega_p} \tag{16}$$

and

$$\chi = F(\alpha,s)q^2|R\beta'|^{3/2}\frac{c^2}{\omega_p^2}\frac{v_A}{R} \tag{17}$$

The coefficient F is near 2.5 except for the very low shear case ($s < 0.3$) [9]. We have the potential difference due to the off-diagonal transport as

$$\frac{e\Delta\phi}{T} \approx \frac{3F^2}{2\,q} \tag{18}$$

which is around 2 for the usual tokamak discharges. The potential difference is spontaneously established, the magnitude of which is about twice of the ion temperature. The toroidal rotation velocity for this potential difference is estimated as

$$v_{\phi *} = \frac{qR}{a}\frac{\rho_i}{a}v_{th} \tag{19}$$

where ρ_i is the ion gyro radius. The off-set of the toroidal rotation at the balanced-injection has been confirmed by experiments [16]. It is shown from Eq.(19) that the normalized spontaneous rotation $v_{\phi *}/v_{th}$ is larger for the low current case, if other parameters are unchanged.

3.4 Rotation Drive by Alpha Particles

In the ignited plasmas, energetic alpha particles are generated. This free energy source could be used for the rotation drive. Ohkawa has discussed, if majority of alpha particles are lost by direct orbit loss (i.e., the plasma current I_p is below 3MA), considerable radial potential could be piled up, which can improve the energy confinement time [17]. The rotation drive by alpha has some contribution even in the case that alpha particles are confined in plasmas.

The generated alpha particles has larger poloidal gyro radius, so that the asymmetry with respect to the toroidal direction appears. The particles which move in the direction of the plasma current are subject to the inward shift, while those in the counter direction move outward. Since the source profile of alpha particles, $S_\alpha(r)$, is localized in the center, $\nabla S_\alpha \simeq -S_\alpha/\ell_\alpha$, ($\rho_\alpha$: banana width of α-particles, and ℓ_α: typical localization width) the momentum source in the co-direction occurs by the alpha-particle heating as

$$M \simeq v_\alpha m_\alpha \sqrt{\varepsilon}\, \frac{\rho_\alpha}{\ell_\alpha} S_\alpha \qquad (20)$$

If this source is balanced with the viscous damping, we have the velocity in the absence of the external source as

$$v_{\phi *} = \frac{a^2}{\mu_\perp} \frac{2\sqrt{\varepsilon}}{m_i n_i v_\alpha V_p} \frac{\rho_\alpha}{\ell_\alpha} P_\alpha \qquad (21)$$

In obtaining Eq.(21), we use the relation of the α-heating power $P_\alpha = (m_\alpha v_\alpha^2/2) S_\alpha V_p$. In the stationary state of ignited plasmas, the energy balance requires the condition $P_\alpha a^2 \chi^{-1} = 3 n_i T_i V_p$. Substituting the expression for P_α, we have

$$\frac{v_{\phi *}}{v_{th}} = \frac{3\chi}{\mu_\perp} \frac{\sqrt{\varepsilon}\,\rho_\alpha}{\ell_\alpha} \frac{v_{th}}{v_\alpha} \tag{22}$$

The normalized ratio $v_{\phi *}/v_{th}$, or $v_{\phi *}/v_A$), does not depends on the mass number of the fuel ions if other parameters are the same. The ratio ρ_α/a is about $(3\mathrm{MA})/I_p$. If one employs a simplified expression as $\ell_\alpha \simeq a$ and values of $T = 10\mathrm{keV}$, $\varepsilon = 0.3$, the spontaneous rotation due to this α-particle drive is estimated as

$$\frac{v_{\phi *}}{v_{th}} \approx \frac{\chi}{3\mu_\perp}\left(\frac{1\mathrm{MA}}{I_p}\right) \quad \text{or} \quad \frac{v_{\phi *}}{v_A} \approx \sqrt{\frac{\beta}{6}}\,\frac{\chi}{3\mu_\perp}\left(\frac{1\mathrm{MA}}{I_p}\right) \tag{23}$$

It is shown that, if the confinement time is improved so that Ip = 10 MA holds, then the spontaneous velocity is in the range of $v_{\phi *} / v_A \approx 10^{-2}$ is expected.

From Eq.(23), we see that the spontaneous drive in the burning plasma increases if the plasma current is reduced. The reduction in the plasma current is realized by the enhanced confinement. The improved confinement is also effective in enhancing the rotation drive efficiency for which the α-particle drive is utilized.

3.5 Impurity Cleaning by Rotation Drive

We finally discuss the plasma purification by use of the rotation drive. It has been discussed that the centrifugal force of the rotation could be useful to repel the impurities from the plasma. For instance, the radial velocity of impurities, $v_{I,r}$, has been obtained as [17]

$$v_{I,\,r} = \frac{m_i Z_I \nu_{ii}}{eB}\left[f_{trap}\frac{E_r}{B} + \frac{m_i}{reB}\left(\frac{E_r}{B}\right)^2 \left\{\left(1 + f_{trap}\right)\frac{A_I}{Z_I A_i} - 1\right\}\right] \tag{24}$$

where the suffix I indicate the impurity, Z is the charge number, A is the mass number, ν_{ii} is the ion-ion collision frequency, f_{trap} is the ratio of the trapped particles ($f_{trap} \simeq \sqrt{\varepsilon}$ holds in the absence of strong radial electric field). The first term in the right hand side is the inward pinch and the second term shows the centrifugal force. From the balance of two terms, we see that the purification is possible (i.e., $v_{I,r} > 0$) if

$$\frac{1}{v_{th}}\left|\frac{E_r}{B}\right| \geq \frac{r}{\rho_i} \frac{f_{trap}}{\left(1 + f_{trap}\right)\frac{A_I}{Z_I A_i} - 1} \tag{25}$$

This condition could be realized only if the condition $Z_I/A_I << 1$ and $f_{trap} << 1$. In this case, the necessary potential difference is estimated as

$$\left|\frac{e\Delta\phi}{T}\right| > \frac{a^2}{\rho_i^2} \frac{f_{trap} Z_I A_i}{A_I} \tag{26}$$

The spontaneous formation of the potential difference and the rotation is evaluated in section 3.3 and 3.4. They are much smaller than the required velocity. The result shows that the large circulating power is required for the plasma purification via rotation drive. The plasma purification seems to be more difficult in comparison with the improved MHD stabilization and confinement.

4. Summary and Discussion

In this article, we discuss the impact of the steady state operation on the improved confinement and advanced tokamak scenarios. The improvement in the MHD stability and confinement, which have been explored by use of the variety in the profile, will require an additional circulating power in the steady state plasmas. Focusing on the role of plasma rotation for the improvement, the concept of the rotation drive efficiency is introduced. The efficiency associated with the direct momentum injection by the beam as well as the spontaneous drive of rotation is investigated.

Several cased are studied. (1) The MHD stability against the high-mode number modes will be improved if the condition for the improved confinement is satisfied. (2) The MHD stability against the global mode, such as the resistive wall mode, puts a severer condition for the profile control. The necessary power for the direct drive is calculated, and is found to be large and intolerable. (3) The rotation velocity, which appears without external momentum source, is estimated. This level is of substantial importance for the advanced concepts in steady state tokamaks. The ignition will give an additional possibility to increase the spontaneous rotation. (4) The purification by the plasma rotation will need large circulating power, and the innovation study is required.

From this study, it is shown that the circulating power for the steady state operation of tokamak reactor will be determined by the efficiency for the current-drive and that for the rotation drive. The simultaneous fulfillment of the high beta value, the good MHD stability and the improved confinement is required. The minimum circulating power is determined by the self-consistency for these conditions. The quantitative analysis for the current drive power has been done extensively. The study in this article is limited to the zero-dimensional estimate for the circulating power, but provides a basis for the quantitative study in the future.

Acknowledgements

Authors would like to thank late Prof. H. Maeda of JAERI for his elucidating discussion. They also acknowledge discussion on the experiments with Dr. K. Ida, Dr. Y. Miura, members of JFT-2M Group, JIPP T-IIU and CHS Group, D III-D Group, JET Team, ASDEX-U Group and W7-AS Team. This work is partly supported by the Grant-in-Aid for Scientific Research of MoE Japan and by collaboration programme of the Advanced Fusion Research Center of Kyushu University.

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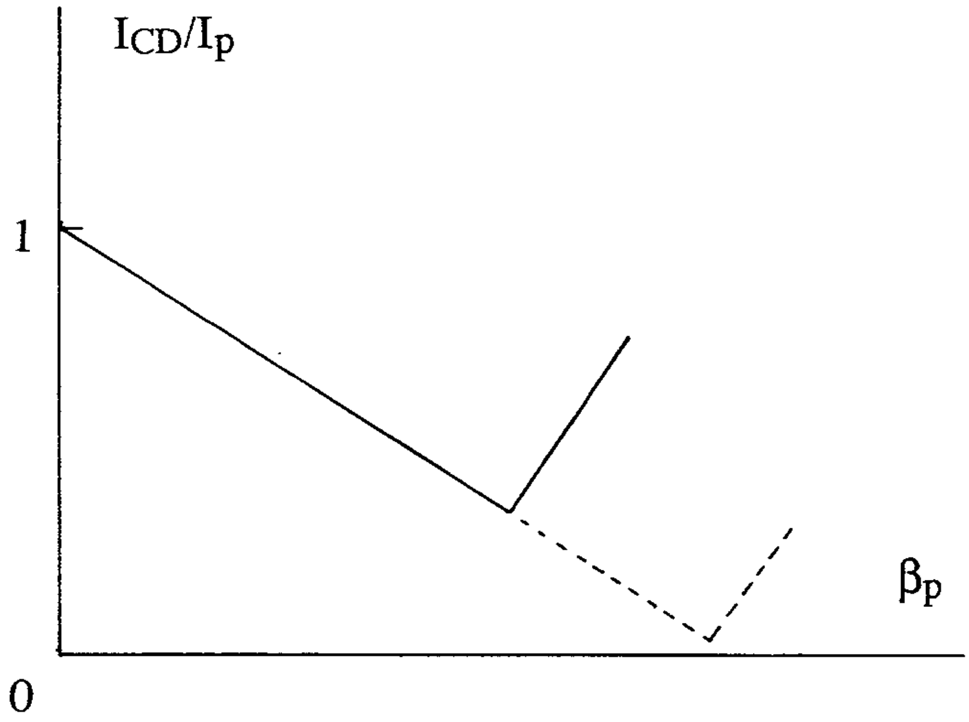
Figure Caption

Fig.1 Schematic illustration of the necessary value of the current drive as a function of β_p.

Table 1 Profile Control

	Motivation	**Damping Process**	**Spontaneous Drive**	**External Drive**	**Events**
Density	(Improved Conf.) Central Burn	D (anom)	V (anom)	Pellet/Beam Fuelling	Sawtooth
Velocity	Improved Conf. MHD Stability	μ_{shear} (anom) μ_{bulk} (NC)	Off-diagonal Transport α-burning	Momentum Injection	Sawtooth MTE ELMs
Current	As above (Thermal Stab.)	$\eta_{\|\|}$ (NC)	BS Current	Current Drive	Sawtooth
Pressure	As above Central Burn (Thermal Stab.)	χ (anom)	Off-diagonal Transport (?)	Heating α-burning	Sawtooth ELMs
Impurity		D (NC & a)	NC pinch	Rotation	ELMs

Fig.1



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