Current Profile Control for High Bootstrap Current Operation in ITER*)

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For the achievement of steady-state fusion power plant, non-inductively current-driven plasma operation should be maintained in tokamak fusion reactors. Total non-inductive current is a summation of bootstrap current proportional to the plasma pressure gradient and externally driven non-inductive current such as neutral beam driven current. Especially in order to establish a commercial reactor, it is necessary to reduce the amount of external current-drive power and to maintain the majority of the plasma current with bootstrap current. Burning plasma has high autonomy, so the change in current density profile including changes in particle and heat transports should be checked. In this study time-evolution analysis of the current density profile for burning plasmas in the ITER machine has been conducted by using 2.0-dimensional equilibrium, 1.5-dimensional-transport code (TOTAL code). Here current-diffusive ballooning mode model was adopted as a heat transport model. It is concluded that external current-drive is required both in the center and near the periphery of the plasma in order to maintain steady-state profiles of temperature and density with high bootstrap current fraction.

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1. Introduction

In tokamak fusion reactors, burning plasmas should be maintained by only non-inductive current-drive for the achievement of steady-state economical reactors. The total non-inductive current is a summation of bootstrap current proportional to the plasma pressure gradient and externally driven non-inductive current such as neutral beam driven current. In order to establish an economical steady-state reactor, it is necessary to reduce the amount of external current-drive power and to maintain the majority of the plasma current with bootstrap current. Plasma parameters such as plasma current I_p, safety factor q, transport coefficient χ and so on, are highly correlated to each other. Therefore it is needed to consider the current density profile with steady and stable plasma profiles including changes in particle and heat transports.

2. Analysis Method

In this study we conducted time-evolution analysis of the current density profile of burning tokamak plasmas by using 2-dimensional equilibrium, 1-dimensional transport code (TOTAL code [1]). The flowchart of this code is shown in Fig. 1. Plasma particle density is maintained constant in time in the present study. We assume that the reactor size is that of ITER. Main reactor parameters are shown in Table 1.

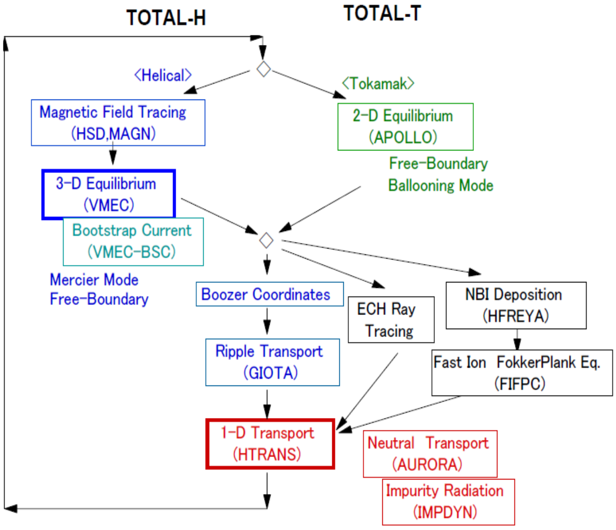

Fig. 1 TOTAL code flowchart.

Table 1 ITER-like reactor parameters.

R_p [m]	a_p [m]	B_t [T]	δ	κ
6.2	2.0	5.3	0.33	1.75

The simulation of hybrid operation scenarios with high bootstrap current fraction in ITER has been performed using various integrated code in Ref. [2]. Here, we focused on the steady state control of high bootstrap current by adjusting current-drive position in the center and at

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the periphery of the plasma in our integrated code TOTAL.

First, we performed iterative computation considering the difference between trial value and target value of the total plasma current, such that the current profile becomes consistent with the given profile of the safety factor. After this plasma equilibrium iteration analysis, we evaluated the bootstrap current ratio and the total steady-state current density profile obtained from both the external driving current and the bootstrap current given in the end.

Total radio frequency heating power is 20 MW. The assumed profile of radio frequency heating power is shown in Fig. 2. The initial temperatures of ion and electron are assumed parabolic and 10 keV at the center of plasma. The initial safety factor profile $q\,(\rho)$ is set as positive shear with $q(0) = 1.0$. External current profile can be defined arbitrary. We assumed the external driven-current profile as $j_{\mathrm{ext}} \sim j_{\mathrm{c}} + j_{\mathrm{h}}$,

$$j_{\mathrm{c}} \approx C_{\mathrm{c}}(1-\rho^2)^{\alpha}, \tag{1}$$

$$j_{\mathrm{h}} \approx C_{\mathrm{h}}\left\{1-(\rho-\rho_{\mathrm{h}})^2\right\}^{\alpha}, \tag{2}$$

where j_{c} is external current driven at the plasma center, and j_{h} is external current driven near the half normalized minor radius ρ_{h}. Constants C_{c} and C_{h} were typically 3 and 500, respectively. It is clarified that it is possible to get rather high bootstrap fraction without half-radius current j_{h}, but impossible to be maintained for a long time. By adjusting the intensity, the position and the width of j_{h}, we can find steady-state high-bootstrap-current profile.

When we assume high safety factor without current-drive in the center of plasma, which is weak poloidal magnetic field, there is a problem that the confinement of fast particle becomes worse [3]. We studied two simulation cases; driving current only in the center of plasma, and both in the center and at the half normalized minor radius of plasma.

In order to get high bootstrap current, the internal transport barrier (ITB) is required, and here we used current-diffusive ballooning mode (CDBM) model [4, 5] as a heat transport model. Thermal diffusion coefficient χ is

$$\chi = \chi_{\text{neoclassic al}} + \chi_{\text{anomalus}}, \tag{3}$$

$$\chi_{\text{anomalus}} = F(s,\alpha)\alpha^{3/2}\frac{c^2}{\omega_{\mathrm{pe}}^2}\frac{v_{\mathrm{A}}}{qR}, \tag{4}$$

$$F = \begin{cases} \dfrac{1}{\sqrt{2(1-s')(1-2s'+3s'^2)}} & \text{for} \quad s' = \hat{s}-\alpha < 0, \\[2ex] \dfrac{(1+9\sqrt{2}s'^{5/2})}{\sqrt{2}(1-2s'+3s'^2+2s'^3)} & \text{for} \quad s' = \hat{s}-\alpha > 0, \end{cases} \tag{5}$$

$$s = \frac{r}{q}\frac{\mathrm{d}q}{\mathrm{d}r}, \tag{6}$$

$$\alpha = -q^2 R\frac{\mathrm{d}\beta}{\mathrm{d}r}, \tag{7}$$

where F is shape factor, c is the velocity of light, ω_{pe} is the electron plasma frequency, q is the safety factor, R is the plasma major radius, r is minor radius, v_{A} is the toroidal Alfven velocity, s is magnetic shear, and α is pressure gradient index. The characteristic of CDBM model is that anomalous transport coefficient becomes small when the magnetic shear is weak or negative.

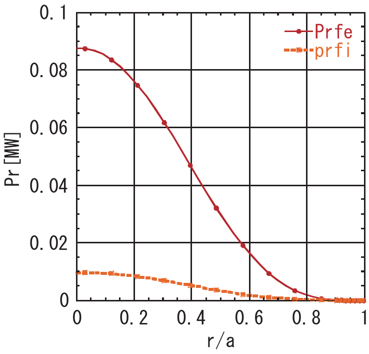

Fig. 2 Profile of external electron heating power P_{rfe}, and ion heating power P_{rfi}.

3. Simulation Results

Figure 3 shows the case of driving plasma current both in the center and at the half normalized minor radius $r/a = 0.5$ of plasma. Here, assumed amounts of D, T and he-

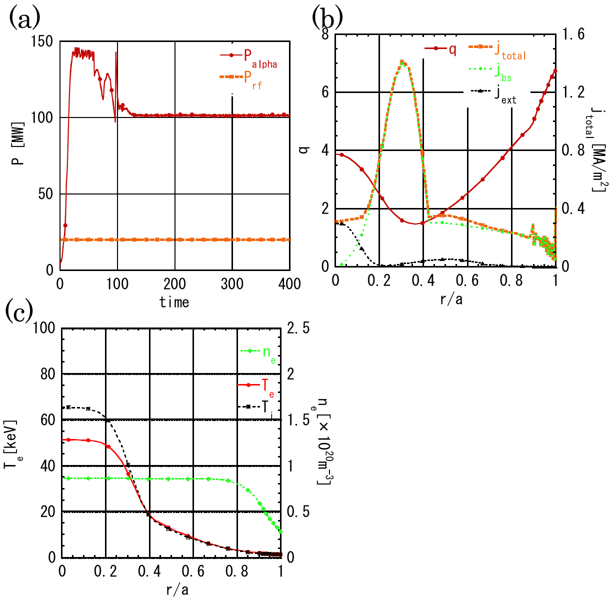

Fig. 3 The case of driving current both in the center and at the half normalized minor radius $r/a = 0.5$ of plasma. (a) Time evolution of alpha heating power P_{alpha} and external heating power P_{rf}. (b) Profiles of safety factor q, total current density j_{total}, bootstrap current density j_{bs} and external current density j_{ext}. (c) Profiles of electron temperature T_{e}, ion temperature T_{i} and electron density n_{e}.

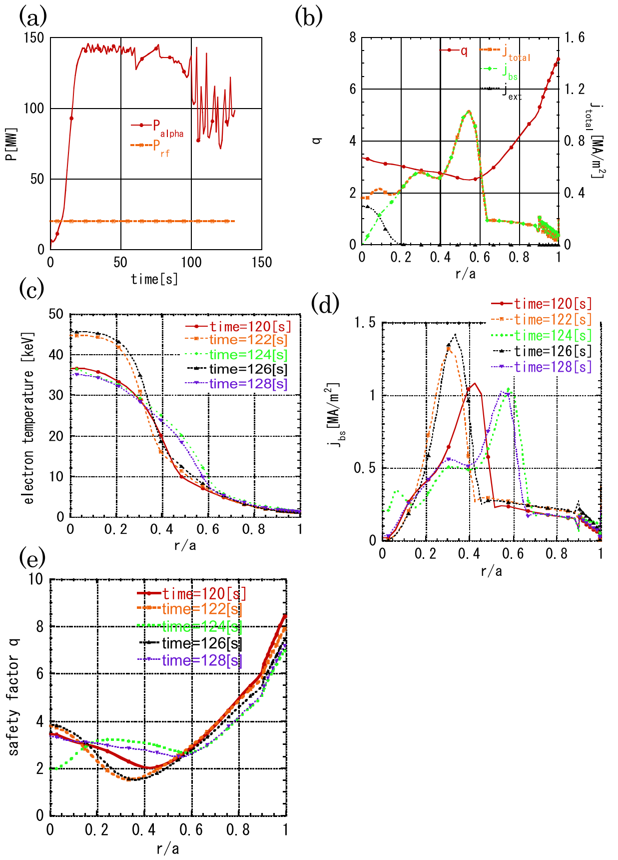

Fig. 4 The case of driving a current only in the center of plasma. (a) Time evolution of alpha heating power P_{alpha} and radio frequency heating power P_{rf}. (b) Profiles of q, j_{total}, j_{bs} and j_{ext}. (c) Time evolution of electron temperature profile. (d) Time evolution of bootstrap current density profile. (e) Time evolution of safety factor profile.

lium are about 45, 45 and 10%, respectively. In this case, the ratio of the bootstrap current (I_{bs}) to the total plasma current (I_{p}), $I_{\mathrm{bs}}/I_{\mathrm{p}}$ is 0.945 and profiles of temperature and electron density can be maintained throughout more than 200 second. In this case, the peak position of bootstrap current density and the minimum position of safety factor are almost same.

Figure 4 shows the case of driving current only in the plasma center. In this case, the bootstrap fraction $I_{\mathrm{bs}}/I_{\mathrm{p}}$ is higher than the case of driving current both in the center and at the half normalized minor radius. The maximum fraction $I_{\mathrm{bs}}/I_{\mathrm{p}}$ is 0.981. However, in this case the alpha heating power is fluctuating. It is reported form the previous simulation study [6] using CDBM model that because of diffusion of current, only central current-drive is not sufficient to maintain steady-state current profile. Though the simulation code used here does not include current diffusion equation, same phenomenon comes about from quasi-stationary transport changes. Anomalous transport coefficient is small when the magnetic shear is weak or negative in CDBM model. In this case, there is substantial difference between the minimum position of the safety factor obtained from the plasma equilibrium and that position obtained including bootstrap current calculated from plasma transport in the next time step. Since the plasma pressure is modified by the change in q profile due to bootstrap current change, the peak of bootstrap current density profile moves.

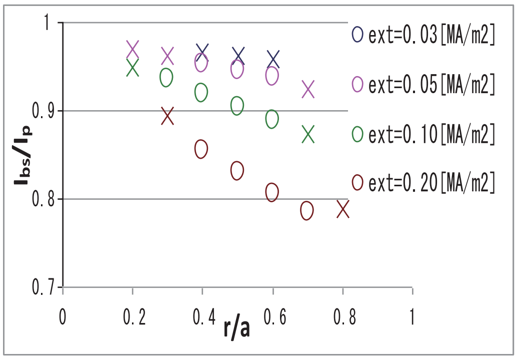

Fig. 5 Relationship between the external current drive position and the bootstrap current.

Figure 5 shows relationship between the external current drive position and bootstrap current ratio to total plasma current. Horizontal axis is the position of external current density peak. The external current is driven both in the center and near the half-radius of the plasma. The central driven current density j_{c} (Eq. (1)) is fixed, and the half-radius current density j_{h} (Eq. (2)) is changed.

In Fig. 5, the symbol of circles corresponds to the case that steady-state profiles can be maintained. The time evolution of plasma parameter is calculated and the figure similar to Fig. 3 is obtained in the case that the temperature and density profiles can be maintained in steady-state. The symbol of crosses corresponds to the case that steady-state profiles cannot be maintained. When the peak position of bootstrap current density is about $r/a = 0.3$ and the current density is about 1.4 MA/m^2, external current drive is required more than 3.6 percent of the bootstrap current outside the peak position of bootstrap current density in order to maintain steady-state current profile.

4. Summary

We assumed initial q profile and determined necessary driven current density profile obtained by subtracting bootstrap current density profile from total current profile. The bootstrap current relevant to plasma pressure gradient is determined through the plasma transport coefficient. The total current profile is estimated by the calculated bootstrap current and required external driven current, the next-step q profile is determined by toroidal equilibrium analysis iteratively. Since there is substantial difference between the minimum position of the safety factor obtained from the plasma equilibrium and that position obtained including bootstrap current calculated from plasma transport in the next time step, the plasma pressure is modified by the change in q profile due to bootstrap current change in the case of driving current only in the plasma center. We concluded that to maintain steady-state temperature and density profiles of ITER-like plasmas with high bootstrap current ratio in the present model, external current-drive is required both in the center and around the periphery of the plasma. External driven current density required is more than 3.6 percent of the bootstrap current density. The position of external driven current should be outside the peak position of bootstrap current density in order to maintain steady-state current profile.

In this analysis, internal transport barrier (ITB) on density profile was not included. We would like to consider the effect of density-ITB on bootstrap current profiles in the future.

[1] K. Yamazaki and T. Amano, Nucl. Fusion **32**, 633 (1992).
[2] C.E. Kessel, G. Giruzzi *et al.*, Nucl. Fusion **47**, 1274 (2007).
[3] T. Suzuki, J. Plasma Fusion Res. **83**, 434 (2007) (in Japanese).
[4] K. Itoh *et al.*, Plasma Phys. Control. Fusion **36**, 279 (1994).
[5] A. Fukuyama *et al.*, Plasma Phys. Control. Fusion **37**, 611 (1995).
[6] A. Fukuyama, J. Plasma Fusion Res. **79**, 1117 (2003) (in Japanese).