Influence of Safety Factor Profile on Bootstrap Current Fraction in Tokamak Fusion Reactors*)

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To achieve a steady-state fusion power plant, non-inductive current-driven plasma operations should be maintained in tokamak fusion reactors. To establish an economical steady-state reactor, the bootstrap current must be enhanced to cover the majority of the plasma current and reduce the amount of externally driven current. The bootstrap current (BS) is affected by the safety factor (q) profile through transport; however, it is not known how changes in the safety factor profile affect the bootstrap current fraction. We conducted time-evolution analyses of the current–density profile for burning tokamak plasmas using a two-dimensional equilibrium, one-dimensional transport code (TOTAL code) with the current-diffusive ballooning mode (CDBM) model as the heat transport model. The effect of the safety factor profile on the BS current fraction $I_{\mathrm{BS}}/I_{\mathrm{p}}$ was evaluated for ITER-like plasmas. After various analyses for different q profiles, we conclude that the most effective way to increase the BS current fraction is to increase the minimum value for the safety factor. In this ITER simulation based on the CDBM model with 20-MW heating power, a maximum BS fraction of 0.6 was obtained using a central q-value of 10.0, a surface value of 6.0, and a minimum value of 3.0.

Keywords: total code, bootstrap current fraction, safety factor profile, current-diffusive ballooning mode

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1. Introduction

To achieve an economical steady-state tokamak fusion reactor, burning plasmas should be maintained only by the non-inductive current drive. The total non-inductive current is the sum of both the bootstrap current, which is proportional to the plasma pressure gradient, and an externally driven non-inductive current such as a neutral beam-driven current. To establish an economical steady-state reactor, the bootstrap current needs to be enhanced to cover the majority of the plasma current and reduce the amount of externally driven current. The bootstrap current is affected by the safety factor profile through transport; however, it is unknown how changes in the safety factor profile affect the bootstrap current fraction. Currently, the dependence of bootstrap current fraction on the safety factor profile must be estimated.

2. Analysis Method

In this study, we conducted time-evolution analyses of the current–density profile of burning tokamak plasmas using a two-dimensional equilibrium, one-dimensional transport code (TOTAL code [1]). The flowchart of this code is shown in Fig. 1. In the present study, the plasma particle density was maintained constant in time. We assumed that the reactor size was similar to that of ITER; the main reactor parameters are shown in Table 1.

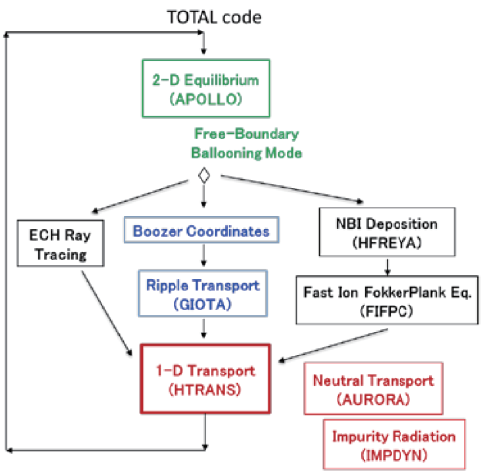

Fig. 1 TOTAL code flowchart.

Table 1 Table1 ITER-like reactor parameters.

R_{p} [m]	a_{p} [m]	B_{t} [T]	I_{P}[MA]	δ	κ
6.2	2.0	5.3	6~13	0.33	1.75

In our previous paper [2], we obtained steady-state plasmas with high bootstrap current fractions by varying the externally driven current–density profile. It was concluded that, to maintain steady-state profiles of temperature and density with a high bootstrap current fraction, an external current drive is required both in the center and

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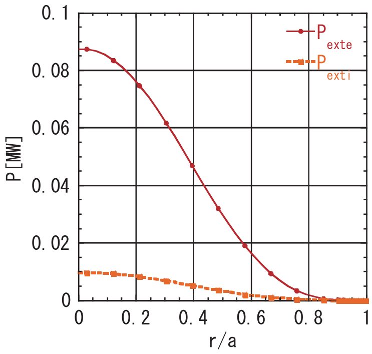

Fig. 2 Profiles of external electron heating power P_{exte} and ion heating power P_{exti}.

near the periphery of the plasma.

Here we focused on the dependence of the bootstrap current fraction on the safety factor (q) profile in the integrated code TOTAL.

First, we performed computational iterations to obtain a plasma current profile that was consistent with a given positive shear q profile while maintaining the total plasma current constant. After alpha heating power became sufficiently large to sustain burning, the initial positive shear q profile was gradually changed to a negative shear q profile. Then, the steady-state total current-density profile and the bootstrap current fraction were evaluated.

The total external heating power was 20 MW. The assumed profile for this external heating power is shown in Fig. 2. The initial temperature profiles for ions and electrons were assumed to be parabolic.

In this study, the q profile can be arbitrarily defined. We assumed the following q profile,

$$q = q_0(1 - x^{2a})^b + q_a x^{2c}, \tag{1}$$

where q_0 is the safety factor in the center of the plasma, and q_a is the safety factor at the plasma edge. The exponents a, b, and c are constants.

First, the plasma current profile was obtained from a given q profile via equilibrium analysis. Then, the external current profile was obtained by subtracting the bootstrap current profile from the total plasma current profile.

We performed simulations by varying the safety factor at the plasma edge q_a between 3.0 and 6.0, the safety factor at the center of the plasma q_0 between 2.0 and 10.0, the minimum value of the safety factor q_{min} between 1.25 and 3.0, and the position of the minimum q value $r_{q_{min}}$ between 0.45 and 0.68. The reference configuration was described by $q_0 = 4.0$, $q_a = 6.0$, $q_{min} = 1.25$, and $r_{q_{min}} = 0.60$. In this reference case, the total plasma current was 8.0 MA.

To obtain a high bootstrap current, an internal transport barrier (ITB) is required; here we used the current-diffusive ballooning mode (CDBM) model [3, 4] as the heat transport model. The thermal diffusion coefficient χ is given by

$$\chi = \chi_{neoclassical} + \chi_{anomalus}, \tag{2}$$

$$\chi_{anomalus} = 12 \times F(s, \alpha)\, \alpha^{3/2} \frac{c^2}{\omega_{pe}^2} \frac{v_A}{qR}, \tag{3}$$

$$F = \begin{cases} \dfrac{1}{\sqrt{2(1-s')(1-2s'+3s'^2)}} & \text{for} \quad s' = \hat{s} - \alpha < 0, \\ \dfrac{(1+9\sqrt{2}s'^{3/2})}{\sqrt{2}(1-2s'+3s'^2+2s'^3)} & \text{for} \quad s' = \hat{s} - \alpha > 0. \end{cases} \tag{4}$$

$$s = \frac{q}{r}\frac{dq}{dr}, \tag{5}$$

$$\alpha = q^2 R \frac{d\beta}{dr}, \tag{6}$$

where F is the 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 the minor radius, v_A is the toroidal Alfven velocity, s is magnetic shear, and α is the normalized pressure gradient. A characteristic feature of the CDBM model is that the anomalous transport coefficient becomes small when the magnetic shear is weak or negative.

Unlike an earlier study [2], we assumed here rather low-density and low-beta plasmas, leading to achieved bootstrap current fractions of less than ~0.5. By increasing the average electron density from 5×10^{19} m^{-3} to 10^{20} m^{-3}, the fraction increases from ~0.4 to ~0.7. By slightly adjusting the radial q-profile to avoid an external inverse current drive and assuming improvements in plasma confinement, this fraction can be increased to around 0.9.

To evaluate the validity of our bootstrap current code, we compared our results with ITER simulation results using the CRONOS suite [5]. Both bootstrap current codes are based on NCLASS. By assuming the same plasma temperatures, densities, and negative magnetic shear profiles, we obtained almost the same bootstrap current–density profiles. The bootstrap current fraction obtained from the TOTAL code was ~0.7, which is the same as the CRONOS result.

3. Simulation Results

In this analysis, the bootstrap current fraction is defined by the ratio of the bootstrap current (I_{BS}) to the total integrated current (I_P) without considering the negative current-drive requirement. When the total current I_P* is calculated by integrating the absolute current density, the bootstrap fraction can be defined as I_{BS}/I_P*.

Figure 3 shows the dependence of I_{BS}/I_p on q_a for q_0 = 2.0 - 10.0. When q_a changes from 3.0 to 6.0 with q_0 = 10.0, the bootstrap current fraction I_{BS}/I_p (I_{BS}/I_p*) increases from 28.0% (28%) to 36.0% (31%). This is because the plasma current required near the plasma edge decreases.

Figure 4 shows the dependence of I_{BS}/I_p on q_0 for q_{min} = 1.25 - 3.0. When q_0 changes from 4.0 to 10.0 with q_{min} = 1.25, the fraction I_{BS}/I_p (I_{BS}/I_p*) increases from 30.2% (24%) to 36.0% (31%). The plasma current required in the center decreases, as shown in the figure.

Figure 5 shows the dependence of I_{BS}/I_p (I_{BS}/I_p*) on q_{min} for $r_{q_{min}}$ = 0.45, 0.60, and 0.68. When q_{min} changes

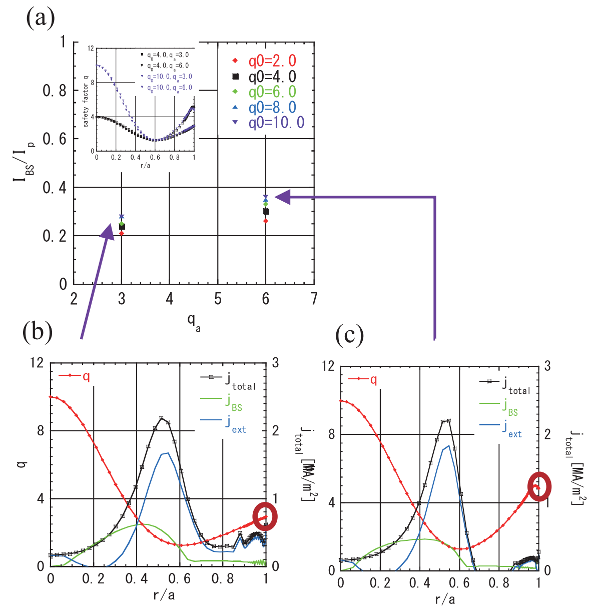

Fig. 3 Effects of changing q_a. (a) Dependence of I_{BS}/I_p on q_a value. (b) Radial profiles for $q_a = 3.0$. (c) Radial profiles for $q_a = 6.0$. Radial profiles are for safety factor q, total current density j_{total}, bootstrap current density j_{bs}, and external current density j_{ext}.

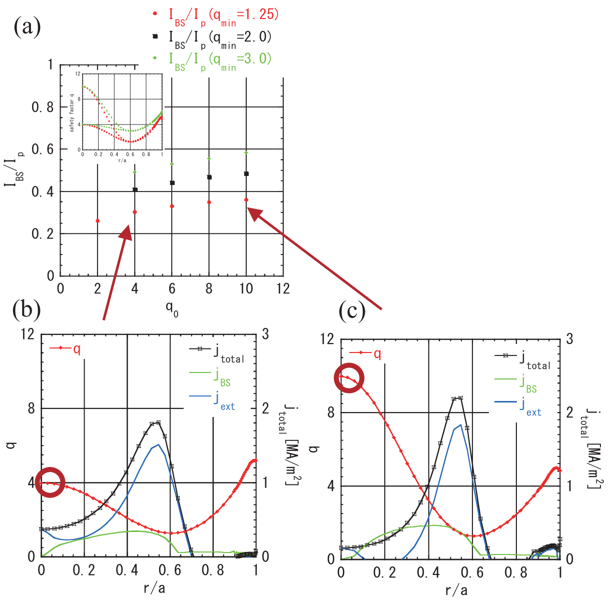

Fig. 4 Effects of changing q_0. (a) Dependence of (a) Dependence of I_{BS}/I_p on q_0. (b) Radial profiles of q, j_{total}, j_{bs}, and j_{ext} for $q_0 = 4.0$. (c) Radial profiles for $q_0 = 10.0$.

from 1.25 to 3.0 with $r_{q_{min}} = 0.60$, I_{BS}/I_p increases from 30.2% (24%) to 48.9% (48.9%). At lower q_{min}, the pressure gradient at ITB is larger (see left figure); however, the local poloidal magnetic field around ITB is higher than that at high q_{min}. The bootstrap current density is proportional to the pressure gradient over the local poloidal magnetic field. Therefore, the BS current at low q_{min} is smaller than that at high q_{min}.

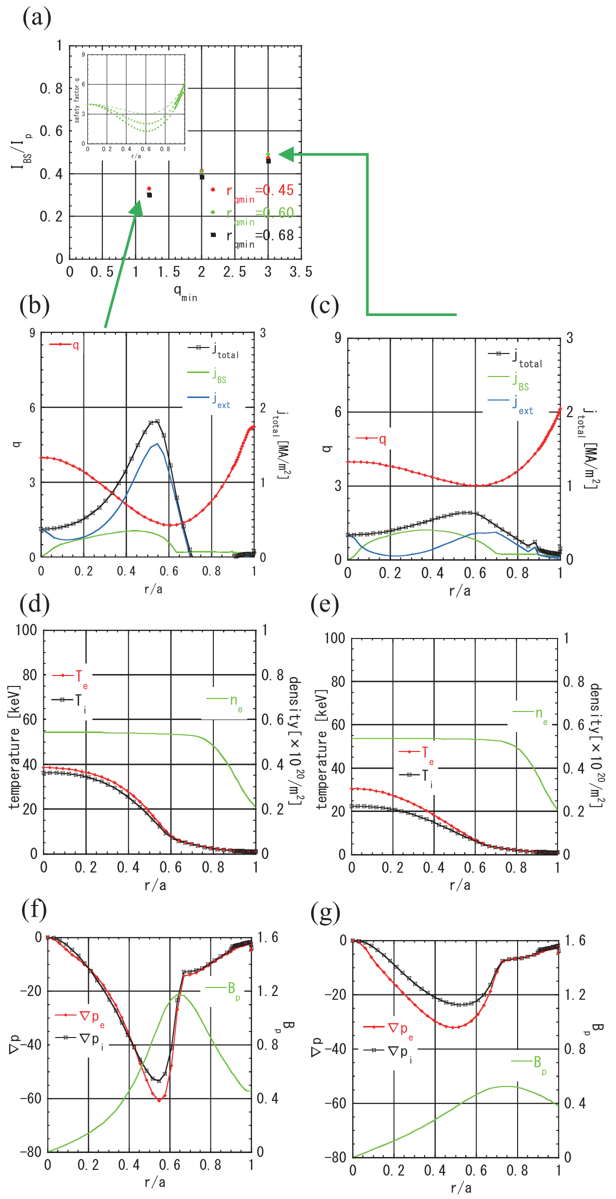

Fig. 5 Effects of changing q_{min}. (a) Dependence of I_{BS}/I_p on q_{min}. Left figures (b), (d), and (f) are for $q_{min} = 1.25$, and right figures (c), (e), and (g) are for $q_{min} = 3.0$. (b) and (c) profiles of q, j_{total}, j_{bs}, and j_{ext}. (d) and (e) profiles of electron temperature T_e, ion temperature T_i, and electron density n_e. (f) and (g) profiles of electron pressure gradient ∇p_e, ion temperature pressure gradient ∇p_i, and poloidal magnetic field B_p.

Figure 6 shows the dependence of I_{BS}/I_p on $r_{q_{min}}$ for $q_{min} = 1.25$ - 3.0. When $r_{q_{min}}$ is reduced from 0.68 to 0.48 with $q_{min} = 3.0$, the BS fraction I_{BS}/I_p ($I_{BS}/I_p{}^*$) increases from 46.0% (46%) to 47.5% (47.5%). Changes in I_{BS}/I_p in response to changes in $r_{q_{min}}$ are not significant compared with those caused by changes in q_{min}, q_0, or q_a.

The effects of the q-profile have previously been discussed using JT-60U current-hole data with a simple model [6]; in particular, the dependence $I_{BS}/I_p \propto r_{q_{min}}^{1.5} q_a/q_{min}$ was obtained in that study. However, the dependence obtained here using TOTAL differs from that obtained from the sim-

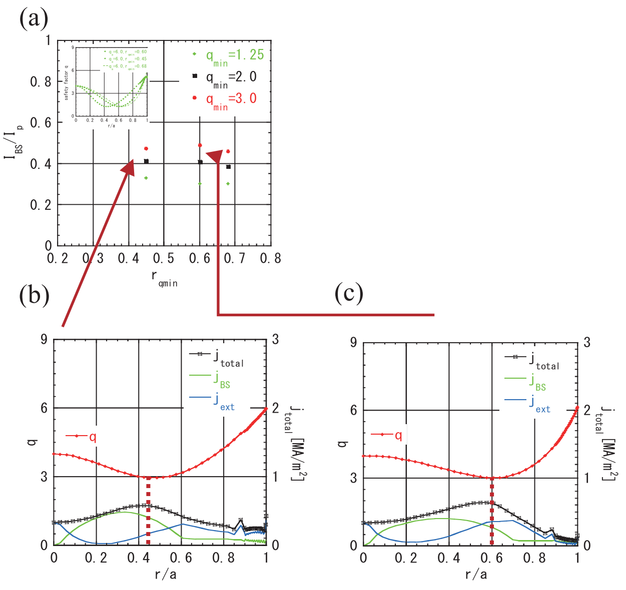

Fig. 6 Effects of changing $r_{q_{\min}}$. (a) Dependence of $I_{\mathrm{BS}}/I_{\mathrm{p}}$ on $r_{q_{\min}}$. (b) Radial profiles of q, j_{total}, j_{bs}, and j_{ext} for $r_{q_{\min}}$ = 0.45. (c) Radial profiles for $r_{q_{\min}}$ = 0.6.

ple model. This difference may be caused by different conditions such as $q_0 < 10$ in TOTAL ($q_0 > 100$ in the simple model) and low $I_{\mathrm{BS}}/I_{\mathrm{p}}$ (< 0.6 in TOTAL but > 0.6 in the simple model).

4. Summary

We evaluated the effects of the safety factor (q) profile on the bootstrap current fraction $I_{\mathrm{BS}}/I_{\mathrm{p}}$ for ITER-like plasmas. The typical bootstrap current fraction $I_{\mathrm{BS}}/I_{\mathrm{p}}$ in ITER with 20-MW heating power is 30.2% in the present reference case (central safety factor q_0 = 4.0, surface safety factor q_a = 6.0, minimum safety factor $q_{\min}$ = 1.25, and minimum q radius $r_{q_{\min}}$ = 0.60).

When the surface safety factor q_a is changed from 3.0 to 6.0, $I_{\mathrm{BS}}/I_{\mathrm{p}}$ ($I_{\mathrm{BS}}/I_{\mathrm{p}}$*) increases from 28.0% (28%) to 36.0% (31%). This is because the plasma current density required around the plasma edge decreases. When q_0 is changed from 4.0 (reference case) to 10.0, $I_{\mathrm{BS}}/I_{\mathrm{p}}$ ($I_{\mathrm{BS}}/I_{\mathrm{p}}$*) increases from 30.2% (24%) to 36.0% (31%), and the required plasma current in the plasma center decreases. By varying the minimum q from $q_{\min}$ = 1.25 (reference case) to $q_{\min}$ = 3.0, $I_{\mathrm{BS}}/I_{\mathrm{p}}$ increases from 30.2% (24%) to 48.9% (48.9%). By varying the q minimum radius from $r_{q_{\min}}$ = 0.68 to $r_{q_{\min}}$ = 0.45, the BS fraction $I_{\mathrm{BS}}/I_{\mathrm{p}}$ ($I_{\mathrm{BS}}/I_{\mathrm{p}}$*) increases from 46.0% (46%) to 47.5% (47.5%).

In the present analysis, the most effective way for increasing $I_{\mathrm{BS}}/I_{\mathrm{p}}$ is to change $q_{\min}$. Changing $I_{\mathrm{BS}}/I_{\mathrm{p}}$ by varying $r_{q_{\min}}$ is not effective compared to changing $q_{\min}$, q_0, or q_a. In this ITER simulation based on the CDBM model with 20-MW heating power, a maximum BS fraction of 58% was obtained using q_0 = 10.0, q_a = 6.0, $q_{\min}$ = 3.0, and $r_{q_{\min}}$ = 0.60.

In the present simulations, a rather modest heating power (20 MW) and a medium density limit (Greenwald factor < 0.7) with the CDBM transport model were assumed for realizing steady-state operations. By increasing the heating power, plasma density, and beta value, higher bootstrap fractions can be realized up to ~0.9, as shown in [2]. The detailed q-profile dependence of the bootstrap current fraction in the high-beta regime will be studied in the future.

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