Study on the steady state Tokamak reactor with combined heating and current drive

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Abstract. The control of burning plasma in the compact ITER is investigated by analyses of the heating and current drives combined with the 1.5D transport simulations. The transport coefficients are determined by analyses in ELMy H mode consistently with IPB98(y,2) scaling and the shear-dependent reduction of diffusivity is introduced in the reversed shear (RS) mode. The heating and current drive by the neutral beam injection and the electron cyclotron wave are considered. The long-pulse operations in ELMy H mode with Q=4.2 and higher are obtained. The loop voltage in the long-pulse operation is less than 0.02V, which corresponds to the burn time 2500 seconds. The steady state operations in RS mode are investigated and operations with Q>6.5 are obtained. The thermal energy confinement time in RS mode increases more than 30% compared with IPB98(y,2) scaling due to the formation of the internal transport barrier. The position of the transport barrier moves toward the plasma edge as the fusion power is increased. It is found that the burning plasma in RS mode has characteristics to organize its profiles by the balance among itself. For both ELMy H and RS modes, the local heating at the region of low diffusivity improves the performance of the plasma. The possibility to obtain high fusion power (>1GW) in RS mode of the compact ITER is discussed.

1. Introduction

In the fusion experimental reactor such as the compact ITER, the steady state or the long-pulse operations are required to achieve their goals, namely to test DEMO-relevant technologies. One of the important objectives of ITER is to study the characteristics of the burning plasmas and establish technology of controlling fusion energy. In the plasma with high fusion gain, alpha power occupies a large portion of the heating power and the large bootstrap current is expected in long-pulse and steady state operations. In these operations, the responses of the plasmas to the external heating and current drive (H&CD) will be different from the experience in the existing machines. In this paper, the responses of burning plasmas to H&CD are studied numerically and the methods to control and optimize performance are investigated. As an example of H&CD methods, a combination of the neutral beam injection (NBI) and the electron cyclotron wave (ECRF) are considered.

In section 2, the model and assumptions of analyses are described. The long-pulse operation in ELMy H mode is investigated in section 3. The analysis on the steady state operation in the reversed shear (RS) mode is presented in section 4. Section 5 is devoted for the summary.

2. Model and Assumption in the analyses

The numerical simulations are performed by using ACCOME code [1] and TOPICS code [2]. ACCOME code provides extensive analysis of H&CD by NBI and ECRF with the gaussian distribution of beam power, consistently with magnetic equilibrium in given profiles of plasma temperature and densities. TOPICS is 1.5D transport simulation code. The analysis is performed by iterations of transferring data between ACCOME and TOPICS until the self-consistent solutions are found.

In the transport analysis, the following transport coefficients are assumed,

$$\chi_{e/i} = \chi_{e/i}^{ano} + \chi_i^{neo}, \quad \chi_{e/i}^{ano} = C \cdot \left(\chi_e^B + \chi_e^{gB}\right) \cdot E(s)$$

$$D_{e/i} = 0.5 \cdot \chi_e \qquad .$$

$$\begin{cases} \chi_e^B = 2.5 \cdot 10^{-4} \left(\dfrac{T_e}{B_T}\right) \cdot q^2 \cdot \left(a_P \dfrac{|\nabla T_e|}{T_e}\right), \quad \chi_e^{gB} = 3.5 \cdot 10^{-2} \left(\dfrac{T_e}{B_T}\right) \cdot q^2 \cdot \dfrac{\rho}{a_P} \left(a_P \dfrac{|\nabla T_e|}{T_e}\right) \\ E(s) = \left\{1 + \exp[\alpha \cdot (s+1)]\right\}^{-1} + \left\{1 + \exp[-\alpha \cdot (s-1)]\right\}^{-1} \end{cases}$$

The coefficient $\chi_{e/i}$ is the electron/ion thermal diffusivity, which consists of anomalous part $\chi_{e/i}^{ano}$ and neoclassical part χ_i^{neo}, where the anomalous part is a sum of Bohm and gyro-Bohm terms [3]. $D_{e/i}$ is the particle diffusion coefficient. The factor $E(s)$ depends on the shear parameter s (=r(dq/dr)/q) and it becomes zero at the minimum of the safety factor for large α (>1) [4]. Therefore, the reduction of diffusivity in RS is represented by $E(s)$ and we use $\alpha = 0.01$ for H mode and $\alpha = 5$ for RS. The coefficient C in the definition of $\chi_{e/i}^{ano}$ is fixed to 0.17 consistently with IPB98(y,2) energy confinement scaling [5]. This value of C is used commonly to ELMy H and RS in the following analyses.

In simulating ELMy H mode, simple descriptions of the edge pedestal and the sawtooth are used, namely reduction of χ, D $\rightarrow$ 0.1m^2/s for $\rho>0.97$ and χ, D $\rightarrow \chi$, D + 1.0m^2/s for q<1. The thermal energy confinement time $\tau_{E,th}$ is obtained as results of transport analyses. The ratio of $\tau_{E,th}$ to the prediction by the confinement scaling law IPB98(y,2), $\tau_{IPB98(y,2)}$, is defined as $H^{eff} = \tau_{E,th}/\tau_{IPB98(y,2)}$, which is used as an indicator of the performance. The particle transport of Helium is adjusted so that $\tau^*_{He}/\tau_{E,th}\sim5$ is satisfied. $Z_{eff}=1.75$ is assumed throughout analyses.

3. Long-pulse operation in ELMy H mode

The plasma parameters of the compact ITER is shown in Table 1. Figure 1 shows NBI injections in our analysis, where two NBI ports are used to on/off-axis H&CD. The off-axis injection is limited by the design of the port and the position in Fig.1 is considered marginal.

A result of transport and H&CD analyses on the long-pulse operation in ELMy-H mode is shown in Fig. 2. The NB power is 100MW, which is distributed 50MW to on-axis and 50MW to off-axis. The Fusion power (P_F) is 420MW, Q=4.2 and H^{eff}=1.0. The volume averaged electron density and temperature are 9 10^{19}m^{-3} and 11keV, respectively. NB-driven and bootstrap currents are 42% and 24% of the plasma current. The loop voltage of the plasma is about 0.02V. This loop voltage leads to the burn time of 2500 seconds in the compact ITER.

The effect of the local heating in ELMy H mode is investigated by injection of ECRF. The additional 20MW is injected to the configuration of Fig. 2 at three different locations separately. Fig.3 shows the electron temperature profiles obtained by transport analyses. The change of temperature at the position of the additional heating is not significant, but global temperature profile changes. The heating at ρ=0.4 does not improve the performance, because the heating near the center affects the q-profile and the region of sawtooth activities is enlarged. The heating at ρ=0.6 improves the fusion power 10% and H^{eff} 5%. The heating at ρ=0.8 is less effective. Therefore, it is considered that the heating at the region of low diffusivity is beneficial to increase the performance. The power distribution of on/off-axis NBI heating is also searched and it is found that the increase of heating at region of low diffusivity improves performance.

Beased on these experiences, the H&CD is optimized. Fig.4 shows a result of optimizations. NBI power 80MW is injected, 30% on-axis and 70% off-axis, and ECRF 10MW is injected separately at ρ=0.5 and 0.6. The H^{eff} and fusion power are increased by 10% and also the plasma loop voltage decreases by 10% compared with the result in Fig. 2.

4. Steady-state operations in RS mode

The steady state operation in RS mode is studied. In the example shown in Fig. 5, the plasma current is 9MA and 80MW NBI is added. The other parameters of this operation are $<T_e>$=13keV, $<n_e>$=8.2 $10^{19}m^{-3}$, H^{eff}=1.37, P_F=521MW and Q=6.5. The transport barrier is formed at ρ=0.65. This improvement of performance is a result of the shear-dependent transport suppression described by E(s).

In Fig. 5, the location of the minimum safety factor, which coincides with the position of the transport barrier, is determined by the bootstrap current. Figure 6 shows the profiles of the temperature and the safety factor for three different electron densities, $<n_{e,19}>$=6.0, 8.2, 9.0. Their fusion powers are 300MW, 521MW and 632MW, respectively. The NBI power and positions are the same as Fig. 5 in three cases. One sees that the position of the transport barrier moves outward as the fusion power increases. The profiles of the plasma parameters are determined by the balance between the pressure, the bootstrap current and the q profile, which are related with each other by the shear-dependent diffusivity. It is considered that the burning plasma in RS mode has strong tendency to organize its profiles by itself.

The improvement in the RS mode is surveyed by the optimization of H&CD. Figure 7 shows the result of adding 20MW ECRF at ρ=0.6. In Fig. 7, the fusion power is 580MW, Q=7.3 and H^{eff}=1.5, which are about 10% larger than the results of Fig.5. Therefore, the local heating at the region of low diffusivity is also useful in RS mode to improve plasma performance.

The steady-state operation in RS mode with high fusion power (>1GW) is investigated by increasing the plasma current to 10MA. Figure 8 is the result for $<n_e>$=1.42 $10^{20}m^{-3}$ and NBI power 82MW, in which 1/3 of NBI power is injected into on-axis and the rest into off-axis. The fusion power is 1.35GW and the fusion gain is 16.5. In Fig. 9, the fusion power (P_F), the ratio of the bootstrap current (I_{BS}/I_P) and the normalized beta (β_N) are shown as functions of the electron density normalized by the Greenwald density limit. The dotted line corresponds to operation point in Fig. 8. This figure shows that it is possible to obtain high fusion power (~1GW) in RS mode of the compact ITER, provided that MHD activities, such as the resistive wall mode, are overcome. Therefore, the optimization of the wall stabilization and active feedback control by the saddle coils will be needed.

5. Summary

The H&CD and transport analyses in the compact ITER are performed. The coefficient in the anomalous diffusion is determined by analyses of ELMy H mode consistently with IPB98(y,2) scaling and the shear-dependent factor is introduced in the transport coefficients to describe the reduction of the diffusivity in RS mode. In ELMy H mode, the operations with the fusion gain more than 4 and the loop voltage less than 0.02V are found. Therefore, the long-pulse operations with burn time more than 2500 seconds are expected. The model provides the steady-state operation in RS mode with H^{eff}=1.37 and Q=6.5. It is found that the position of the tansport barrier depends on the fusion power and it is somewhat insensitive to the external current drive. In both ELMy H mode and RS mode, the local heating in the region of low diffusivity is found beneficial to improve the plasma performance.

Reference

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[3] Taroni, A., et al., Plasma Phys. Control Fusion, 36 (1994)1629.
[4] Ushigusa, K, et al., in Fusion Energy conf. 1998 (Yokohama), IAEA-F1-CN-69/FTP/12.
[5] ITER Physics Basis, Nucl. Fusion 39 (1999) 2137.

Table 1. Main plasma parameters of the compact ITER used in the analysis

Parameter / Operation	Long-pulse	Steady state
Confinement	ELMy-H	RS
Major/Minor radius	6.35m/1.75m	6.5m/1.6m
Elongation/Triangularity	1.74/0.32	2.07/0.54
Plasma current (High power operation)	12MA	9MA (10MA)
Toroidal field	5.37T	5.25T
Fusion power (High power operation)	~500MW	~500MW (> 1GW)
NBI R_{tang} / E_b	6.1m / 1MeV	
EC frequency	170GHz	

Fig. 1. On/off-axis injections of NBI

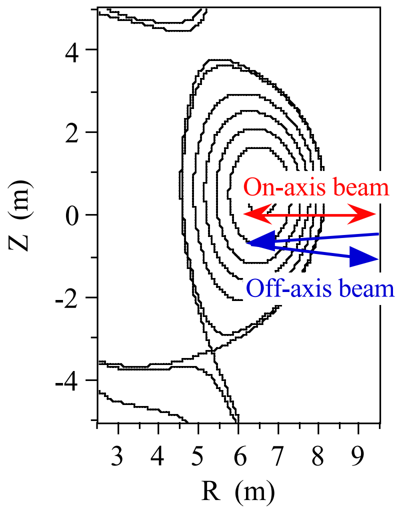

Fig. 2. The profiles of the long-pulse operation in ELMy-H mode. $\langle n_e\rangle=9\ 10^{19}m^{-3}$, $\langle T_e\rangle=11.2$ keV, $H^{eff}=1.0$, $\beta_N=2.3$, $P_F=420$MW.

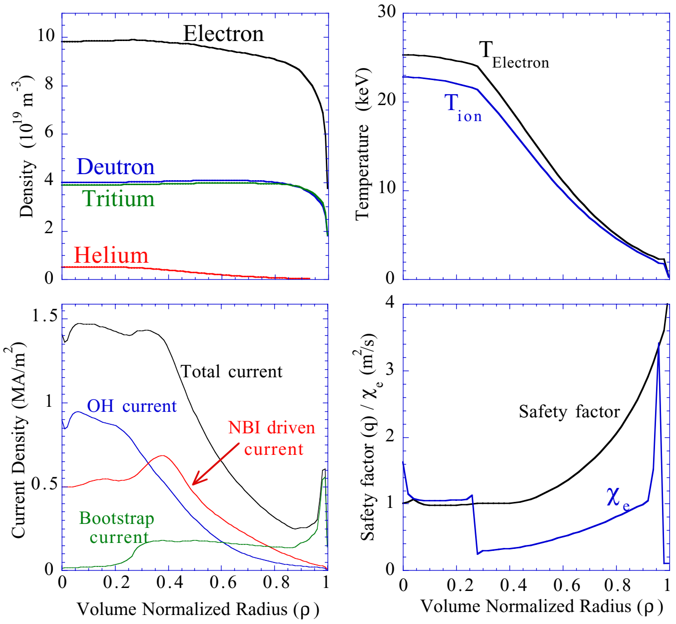

Fig. 3. Positions of local heating by ECRF and resulting temperature profiles

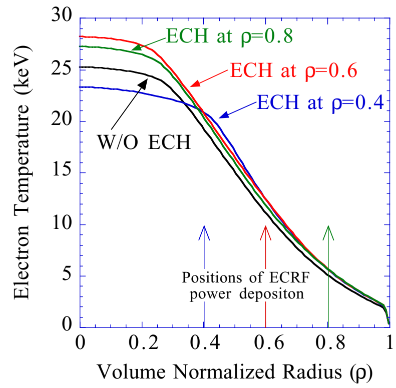

Fig. 4. Profiles obtained by optimized H&CD. NBI heating (on-axis:24MW, off-axis:56MW) and ECRF(ρ=0.5:10MW,ρ=0.6:10MW) are added (a). Resulting current profiles (b) and temperature/safety factor (c). $\langle n_e\rangle=9\ 10^{19}m^{-3}$, $\langle T_e\rangle=11.9$keV, $H^{eff}=1.1$, $P_F=443$MW

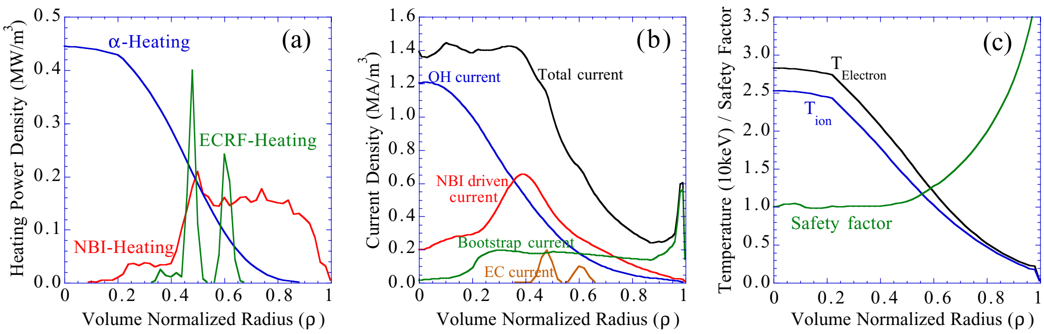

Fig. 5. The profiles of the steady state operation in RS mode.
$\langle n_e \rangle = 8.2\,10^{19} m^{-3}$, $\langle T_e \rangle = 13.3keV$, $H^{eff} = 1.37$, $P_F = 521MW$, $Q = 6.5$

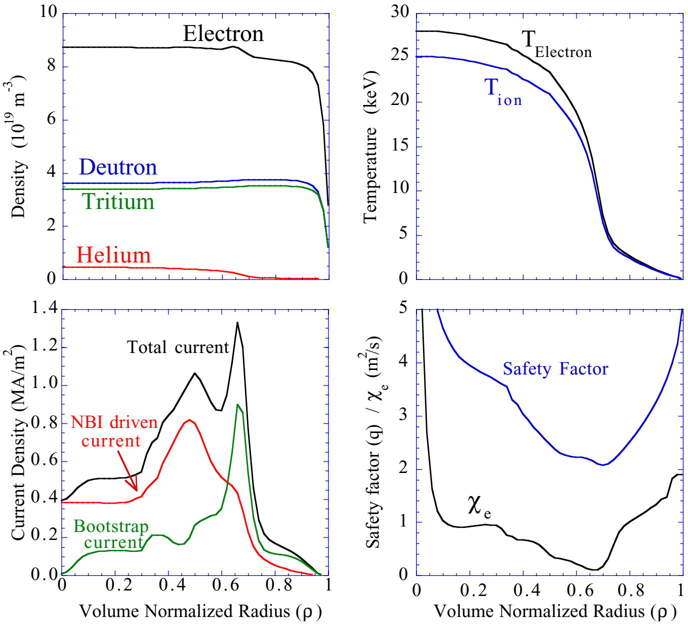

Fig. 6. The profiles of electron temperature and the safety factor in RS mode for different densities, $n_e = 6\ 10^{19}$, $8.2\ 10^{19}$, $9\ 10^{19} m^{-3}$, in which the fusion powers are 300MW, 521MW, 632MW, respectively.

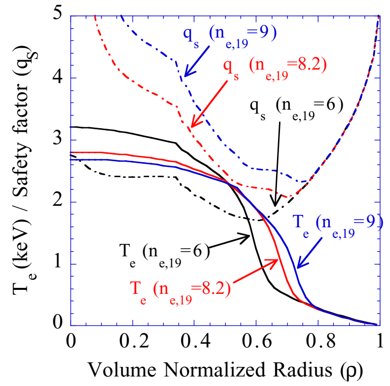

Fig. 7. The improvement of RS operation by adding 20MW local heating at ρ=0.6 by ECRF, heating densities (a), currents (b) and temperature and safety factor (c).
$P_{AUX} = 80MW$ ($P_{EC} = 20MW$, $P_{NBI} = 60MW$), $H^{eff} = 1.5$, $P_F = 581MW$, $Q = 7.3$

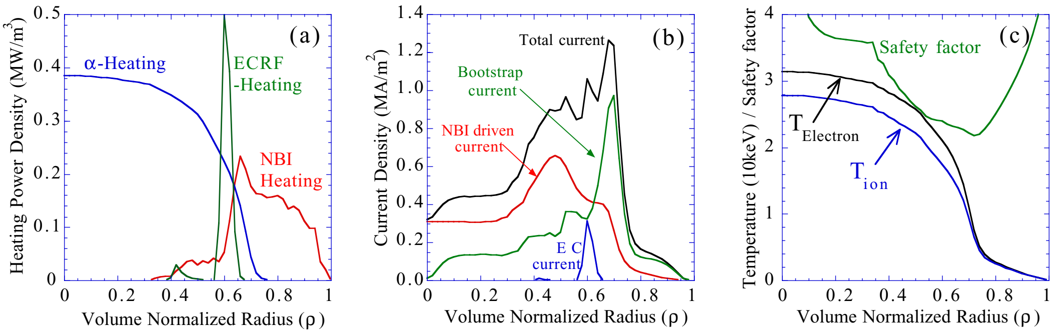

Fig. 8. The profiles of the steady state in RS for the high fusion power operation ($I_P = 10MA$), temperature and safety factor(a) and currents(b).
$\langle n_e \rangle = 1.42\ 10^{20} m^{-3}$, $H^{eff} = 1.4$, $P_{NBI} = 82MW$, $P_F = 1.35GW$

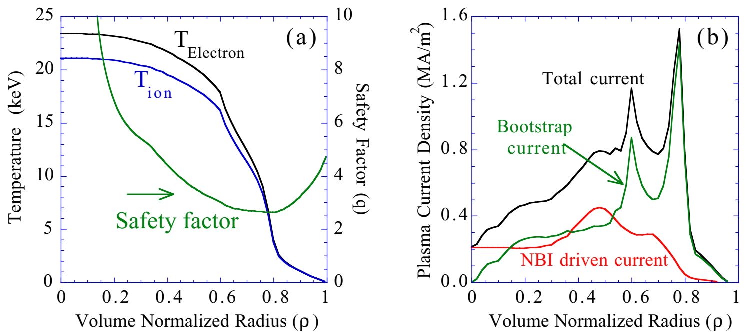

Fig. 9. P_F, I_{BS}/I_P and β_N in the high fusion power operation ($I_P = 10MA$) as functions of the plasma density.