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Profile Control Using RF Wave Heating in KT-2 Tokamak

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Abstract

In this paper, the 100 % non-inductive current drive scenarios are addressed for the steady-state operation on KT-2 tokamak, with the profile control using fast wave and lower hybrid wave as the external tools. Considering the stability, the well-aligned current profiles with a reversed-shear and $q_{min} > 2.0$ has been favorable in high β_p plasma, together with a possibly higher bootstrap current fraction. Therefore, the effects of the auxiliary heating power profile on the control of MHD favorable current profile are evaluated in detail.

1. Introduction

It has been known that the very promising scenario for the steady-state operation of fusion reactor is the reversed-shear and high β_p mode operation, minimizing the non-inductive current drive power requirements [1]. The revered-shear operation mode is related to the second stable regime to high-n ballooning modes. In addition, it has shown the enhanced confinement and, thus, the strong reduction of transports in JET, Tore Supra, and DIII-D [3-5]. The characteristics of this reversed-shear mode is to have the non-monotonic q profile with a reversed region between the magnetic axis and the flux surface of q_{min} along the plasma minor radius. To minimize the current drive powers required externally, the well-aligned current profiles with a possibly highest bootstrap current fraction, consistent with MHD stability, should be preserved in a plasma. Considering the stability, the well-aligned current profile with a reversed-shear and $q_{min}> 2.0$ has been favorable, together with a higher bootstrap current fraction [2]. To control the current profiles driven non-inductively on KT-2 tokamak, two current drive schemes are introduced: (1) lower hybrid current drive(LHCD) and (2) fast wave current drive (FWCD). Therefore, the purpose of this study is to find the possible operation modes of reversed-shear, high β_p, and higher bootstrap current fraction, by the profile control.

2. Physics Modeling for KT-2 tokamak Plasma

To describe the evolution of KT-2 tokamak plasma, the nonlinear fluid equations for density, energy and current diffusion are solved on the flux-surface averaged coordinate. The change of plasma geometry is self-consistently evaluated by the evolving current and pressure profiles of Grad-Shafranov MHD equilibrium equation. A transport model of net radial particle and energy fluxes for the main plasma, is described as the sum of full neoclassical and anomalous transports. Typically, the anomalous transport terms contribute to the neoclassical transport as only the diagonal terms. The anomalous transport coefficients are forced to follow the specific empirical scaling laws, and thus normalized over a global energy confinement time taken as a minimum of either neo-Alcator scaling or ITER L-mode scaling with a higher confinement factor (H_f) [6]. To model the bootstrap current driven in plasma, the neoclassical model of Hirshman [7] is used. To model the power depositions of the incident fast wave and lower hybrid wave on the plasma electrons, we use a relatively simplified analytical models, based on their respective propagation characteristics in the plasma. In case of fast wave, its power deposition rate to electrons is proportional to the local damping rate of fast wave. The power of incident lower hybrid wave is predominantly deposited in outer part of plasma due to the density cut-off of lower hybrid wave in plasma. Therefore the gaussian power deposition profile with a width, Δ_{lh} , and the peak at a minor radius, ρ_{lh},

B_0	2 T	$< n_e >$	0.5 e^{20} m^{-3}
I_p	300 kA	T_{res}	5 keV
R/a	1.4/0.25 m	f_{fw}	20 MHz
κ/δ	1.8/0.6	$n_{\parallel}(lh)$	2.1
T_o/T_b	3/0.3 keV		

Table 1: Input Parameters Used in the Calculations

$\Delta_{aux}(cm) at r_{aux}$=10cm		$r_{aux}(cm) at \Delta_{aux}$=7cm	
case1	12.0	case7	10.0
case2	11.0	case8	11.0
case3	10.0	case9	12.0
case4	9.0	case10	13.0
case5	8.0	case11	14.0
case6	7.0		

Table 2: 11 cases used in the Calculations

is used. As the model of current drive efficiency, we choose the semi-analytical formula by D.A.Ehst and C.F.F.Karney [8] in order to match it to the numerical results.

3. Numerical Results

In this subsection, the plasma heating and 100 % non-inductive current drive scenarios is studied to approach the MHD stable high β_p plasma operation on KT-2 tokamak, with the profile control using fast wave and lower hybrid wave. In addition, the powers required to control these profile are calculated: (1) the power requirement of fast wave current drive (FWCD) is calculated to control q_o to be < 3.0, which is needed to generate the non-monotonic q profile with $q_{min} > 2.0$. (2) In case of lower hybrid wave current drive (LHCD), the required power is evaluated to generate the seed current in off-axis part of plasma, necessary to maintain total plasma current at 300 kA. From the preliminary study, it was found out that the auxiliary heating power of > 3 MW was required to achieve the higher β_N ($\beta_N \equiv \frac{\beta}{I_p/aB}$) operation mode of > 3.0 in KT-2 tokamak parameters of Table 1. The effects of auxiliary lower hybrid wave heating power profile on the establishment of reversed-shear region in off-axis part of plasma, q_{min} and the generation of the higher bootstrap current mode are studied through the variation of Δ_{aux} (7.0 $\sim$ 12.0 cm) and r_{aux} (10.0 $\sim$ 14.0 cm). In table 2, 11 cases used in the calculation are described. In figure 1-(a), q profiles according to the variation of width of auxiliary lower hybrid wave heating power profile when r_{aux} =10 cm (case1-case6) are seen. In these cases, the wider heating power spectrum of auxiliary lower hybrid wave could generate the higher bootstrap current fraction, and, in addition, played a role to increase q_{min} toward > 2.0. Compared to the results of case 2-6, case 1 which generated the highest bootstrap current fraction from 6 cases showed two reversed shear regions of ∇q in the plasma. In figure 1-(b), q profiles according to the variation of peak position of auxiliary heating power profile when Δ_{aux} = 7 cm and P_{aux}= 3 MW (case7-case11) are seen. As the peak position of auxiliary heating power profile move out to the outer part of plasma, the position of q_{min} along the minor radius tended to be pushed out to the plasma outer boundary, which played a decisive role to increase $q_{min} > 2.0$. All cases of figure 1-(b) showed a common feature in generated q profiles that they have two reversed shear regions of ∇q inside the plasma. Furthermore, the second reversed region seemed to extend out to the plasma outer boundary as r_{aux} increases. Figure 2 shows the driven seed current profiles of fast wave and lower hybrid wave, driven bootstrap and total current profiles, and the time-ρ(a minor radius) dependence of q profile for case 2. The auxiliary heating power profile of case 2 generated the bootstrap current fraction of 82 % and the reversed-shear mode with $q_{min} > 2.0$. The fast wave power of 241 kW was required to control q_o to be near 3.0, which generated a seed plasma current of $\sim$ 21 kA ($\sim$ 7 % of total plasma current). The lower hybrid wave power required to generate the rest current of 35 kA in the outer part of plasma necessary to control total plasma current to be 300 kA was 104 kW. The current drive efficiencies of fast wave and lower hybrid wave in case 2 are γ_{fw}=0.042 and γ_{lh}=0.19 A/W-m2, respectively.

4. Summary

In this paper, the full 100 % non-inductive current drive scenarios were studied for the steady-state operation on KT-2 tokamak, with the profile control using fast wave and lower hybrid wave as the external tools. Considering the stability, the well-aligned current profile with a reversed-shear and $q_{min} > 2.0$ has been favorable in high β plasma, together with a possibly higher bootstrap current fraction. Therefore, assuming that the auxiliary lower hybrid wave heating power has the gaussian power deposition profile, the effects of its shape on the generation of MHD favorable current profile were evaluated. But it should be noted that the calculation results presented in this paper were especially very dependent on the modelings of anomalous transport and bootstrap current, and on the ratio of electron and ion thermal conductivity, the power de position models and on the confinement factor (H_f). For example, when H_f= 2.0, 30 % reduced bootstrap current fraction was shown. Therefore, more further extensive parameter study should be carried out for more exact understanding of transport and wave physics.

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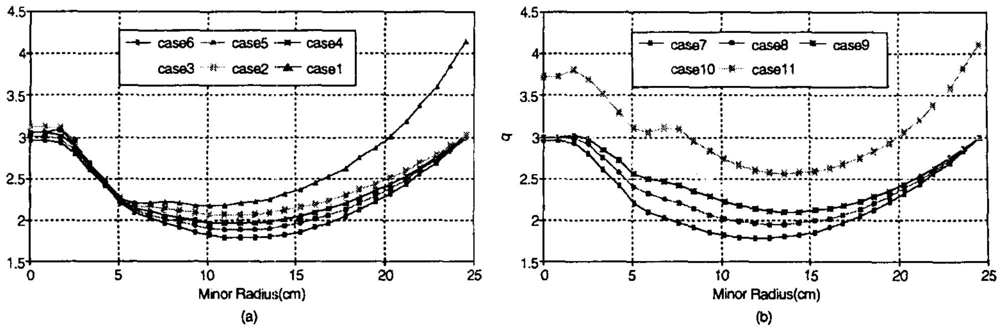

Figure 1: q profiles according to the variation of (a) $\triangle_{aux}$ and(b) r_{aux} at P_{aux} =3.0 MW

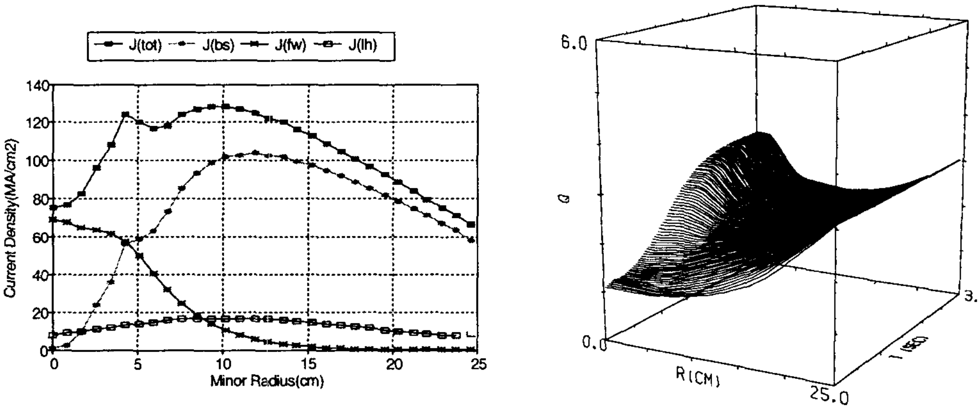

Figure 2: (a) the various driven current profiles along the minor radius at t=3.0sec, and (b) the time and minor radius dependence of q profile when P_{aux}=3 MW, $\triangle_{aux}$=10cm, and r_{aux}=11 cm (case2)