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Control of rotating helical magnetic field penetration into tokamak plasmas using electrode biasing in HYBTOK-II

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Abstract

Detailed measurements of rotating helical field (RHF) have been carried out in a small tokamak device HYBTOK-II in order to know the interaction between the tokamak plasma and RHF. The magnetic pick-up coils were inserted deeply inside the plasma to detect the response profile of tokamak plasma to the RHF. It was found that a large relative velocity between the plasma and RHF poloidal rotation velocities gives rise to a strong attenuation of RHF in the plasma because the large screening current flows around the resonance surface against the externally applied RHF. The electrode biasing was applied so as to increase the relative velocity so that the RHF was strongly attenuated in comparison with unbiased case.

PACS: 52.30.Jb
Keywords: Rotating helical magnetic field; Dynamic ergodic divertor; Electrode biasing; HYBTOK-II

1. Introduction

Dynamic ergodic divertor (DED) is an advanced concept for the control of edge tokamak plasma [1,2]. In contrast to conventional static (stationary) ergodic divertor, an externally applied helical magnetic field rotates in the helical direction. The rotating helical magnetic field (RHF) may decrease the amount of heat and particle flux onto the local target encountered in the conventional tokamak divertor. In the DED concept, it is also expected that the RHF induces the edge plasma rotation due to the screening current around the resonance surface so that the plasma confinement may be improved by the induced shear flow. In addition, a control of particle recycling at the edge in combination with a pump limiter is also planned.

The pioneer experiment to investigate the interaction between the tokamak plasma and RHF has been carried out on a small tokamak device CSTN-IV [3,4]. Penetration processes and the dynamic behavior of RHF in tokamak plasmas have been investigated. In the case of resistive plasmas (Lundquist number $S \sim 230$) such as CSTN-IV, the redistribution of the plasma current due to magnetic island formation induced by RHF was predominantly observed. We have started a new DED experiment on a small tokamak device, HYBTOK-II to study the fundamental processes of DED in a higher-temperature region ($S \sim 5000$) compared with CSTN-IV. Since the magnitude of the screening current has a strong dependence on the electron temperature T_e near the resonance layer (resulting from plasma resistivity $\eta \propto T_e^{-3/2}$), it is expected that the RHF can drive the plasma rotation by means of the large screening current. In the first experiment on HYBTOK-II, we have confirmed the attenuation of the radial component of RHF B_{r1} from the magnetic probe measurement in the plasma

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[5]. It was also found that the penetration process depends also sensitively on the relative poloidal rotation velocity between the tokamak plasma and RHF. Hereafter Ω is used to refer to the relative velocity (i.e. Doppler-shifted frequency of RHF).

In this paper we describe the control (performance) of the penetration process by means of electrode biasing, which can change the natural plasma rotation velocity.

2. Experimental setup

HYBTOK-II is a small tokamak device with a major radius of 40 cm, a minor radius of 12.8 cm and a limiter radius of 11 cm. The device is equipped with insulated gate bipolar transistor (IGBT) inverter power supplies for Joule as well as vertical field coils. In addition, a real-time feedback control of the plasma horizontal position has been employed with digital signal processor. This system makes it possible to keep the plasma horizontal position during applying RHF and electrode biasing. In this experiment the plasma current and toroidal field were set to 4.9 kA and 0.27 T, respectively. The RHF is created by two sets of local helical coils installed outside the vacuum vessel at eight toroidal sections among the 16 sections with the poloidal and toroidal mode numbers of $m = 6$ and $n = 1$. The radial position of helical coils is at $r = 13.5$ cm. In TEXTOR-DED experiment, the perturbation coils will be located on the high field side with poloidal coverage of $\pm 60°$ [6]. These partially located coils will make the poloidal mode spectrum very broad, so that it is difficult to control the stochastic region at the plasma edge. In contrast to TEXTOR, the helical coils cover in a poloidally complete region in HYBTOK-II as shown in Fig. 1 so as to improve the mode quality of RHF compared with that of TEXTOR [7]. These two sets of coils are powered independently by IGBT inverter power supply with a phase difference of 90°. We can control the poloidal rotation direction of RHF by changing the phase difference between two coils. Hereafter the terms 'Case I' and 'Case II' denote the rotation directions of RHF, corresponding to the directions of ion and electron diamagnetic drift, respectively. The frequency of RHF was set to the maximum available frequency of 30 kHz, and then the capacitors were connected in series to the helical coils forming resonant circuits, because the reactive load gives the limitation of coil current in this frequency. The RHF was applied between $t = 10$ and 17 ms, and B_{r1} was 0.8 G at $r = 8.5$ cm in vacuum. The radial profiles of RHF and poloidal field in the plasma were obtained with absolutely calibrated small magnetic probes (radial, poloidal component), which are inserted vertically from the bottom of the vacuum vessel at the section with the helical coils (see Fig. 1). The time series of RHF were digitized with 1 MHz sampling after passing through the integrator. In addition, a triple probe is also installed to measure the floating potential, electron temperature and density. A movable electrode made of titanium, having a diameter of 3 cm and a height of 1 cm, is inserted from the top of the vacuum vessel for the biasing experiment as shown in Fig. 1. A radial electric field is induced by a radial current flowing from the electrode to the vacuum vessel. We have adjusted the biasing voltage and the position of the electrode so as to change uniquely the radial electric field without any drastic change of electron temperature. The DC positive biasing of 60 V gives the time traces of electrode voltage and current shown in Fig. 2(b).

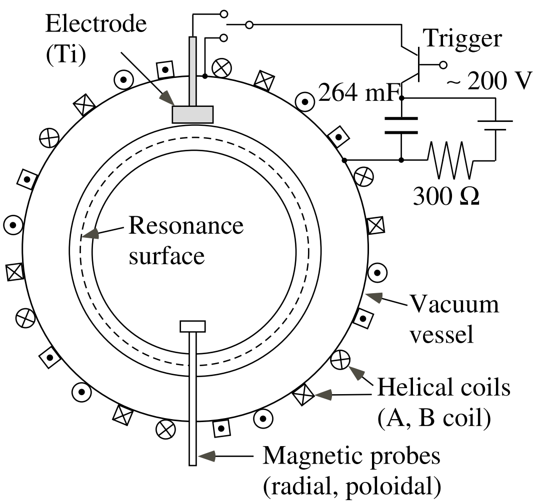

Fig. 1. Schematic view of poloidal cross section of HYBTOK-II. The current directions of helical coils (A, B) are indicated. The electrode and biasing circuit are shown.

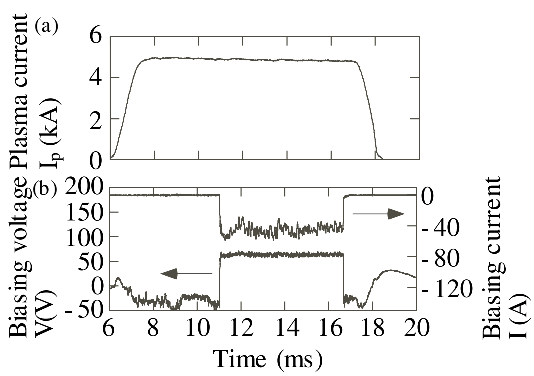

Fig. 2. Time evolutions of (a) plasma current I_p and (b) electrode voltage V and current I. The DC biasing voltage is set to +60 V.

3. Experimental results and discussion

The safety factor q profile measured by the magnetic probe in the plasma is shown in Fig. 3(a), in which the resonance surface of $m/n = 6/1$ is found to be located at $r = 8.5$ cm. From the analysis of the mode spectrum [7] of RHF, it is necessary to consider not only the resonance surface of the main mode but also those of the sideband components ($m = 5$, 7, 8). The resonance surface even in the presence of the electrode biasing is also located at the same position so that the electrode biasing does not give any large modification on the current density profile in this experiment.

The plasma rotation velocity was evaluated from the $E \times B$ drift velocity by using the following method. The plasma potential can be estimated from the formula [8] $V_p = V_f + 3T_e$ (in H_2 plasma), where V_p and V_f are the plasma potential and the floating potential, respectively. The radial profiles of T_e and V_f with and without the electrode biasing are shown in Fig. 3(b) and (c). Using this relation, the radial electric field is obtained from the radial derivative of V_p.

Fig. 4 shows the radial profiles of the $E \times B$ drift velocity with and without the electrode biasing, and the phase velocity of RHF. Here, the electrode is located at $r = 9$–10 cm so as to create a strong inward radial electric field near the resonance surface, where the plasma rotates in the direction of electron diamagnetic drift. This result shows us that the Ω is very much increased when the direction of RHF is set to Case I.

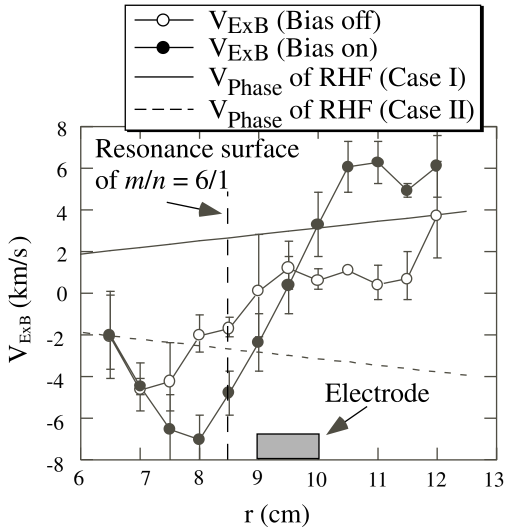

Fig. 4. Radial profiles of the $E \times B$ drift velocity with (●) and without (○) the electrode biasing, and the phase velocity of RHF for $m = 6$. The solid (dashed) line shows the phase velocity in Case I (Case II).

The radial profiles of B_{r1} are shown in Fig. 5, where the open circles, the closed triangles and the closed circles denote the amplitudes in vacuum, with and without the electrode biasing, respectively. The time averaged amplitude of B_{r1} was calculated by using fast Fourier transform technique from $t = 12$ to 17 ms, and the square root of the peak value of 30 kHz is plotted in Fig. 5. Here, the direction of RHF was set to Case I. As Fig. 4 indicates, the Ω becomes large in Case I around the

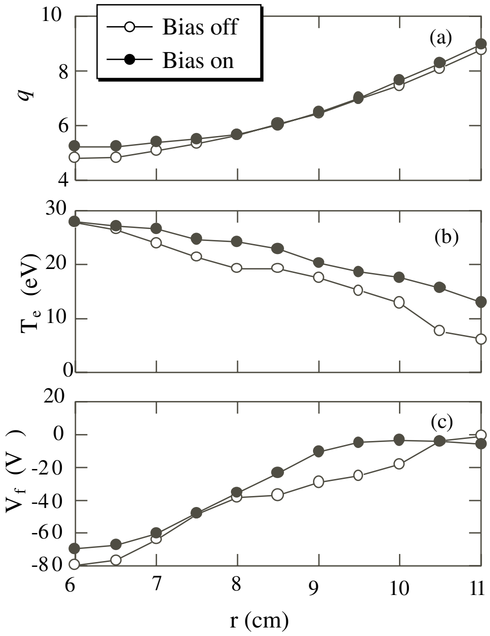

Fig. 3. Radial profiles of (a) q with (●) and without (○) the electrode biasing, (b) electron temperature T_e and (c) floating potential V_f.

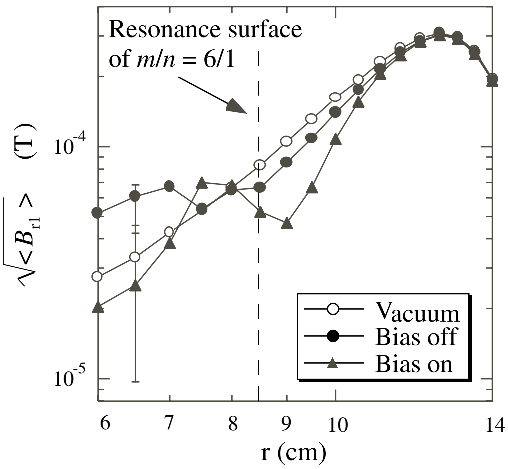

Fig. 5. Radial profiles of B_{r1} in vacuum (○) and in the plasma with (▲) and without (●) the electrode biasing.

resonance surface of $m/n = 6/1$. It is found from Fig. 5 that the large Ω created by the electrode biasing enhances the attenuation of B_{r1} in the plasma. Fig. 5 also shows that the B_{r1} is slightly amplified compared with that in vacuum deeply inside the resonance surface of $m/n = 6/1$. As mentioned above, the re-distribution of plasma current due to the growth of magnetic islands has been found in CSTN-IV. The perturbed plasma current has been detected as an amplification of B_{r1}. Therefore, Fig. 5 shows that the B_{r1} is not screened out completely, although the large screening current flows around the resonance surface. The main mode, $m/n = 6/1$, is focused in this work, however, it is a debatable how the sideband components of RHF, especially $m/n = 7/1$, affect the attenuation of B_{r1}.

Finally, we would like to confirm the change of magnetic reconnection induced by the enhancement of Ω by using the following analysis since Fig. 3(b) indicates that the electrode biasing affects not only the plasma rotation velocity but also the electron temperature. In Ref. [9] the interaction between a rotating tokamak plasma and resonant perturbation field in linear regime has been investigated. The amount of magnetic reconnection when the diamagnetic drift is neglected is given by

$$\frac{\Psi}{\Psi_{\mathrm{full}}} = \frac{1}{1 + \mathrm{e}^{-\mathrm{i}5\pi/8}\lambda\mu_{\mathrm{c}}^{5/4}}, \tag{1}$$

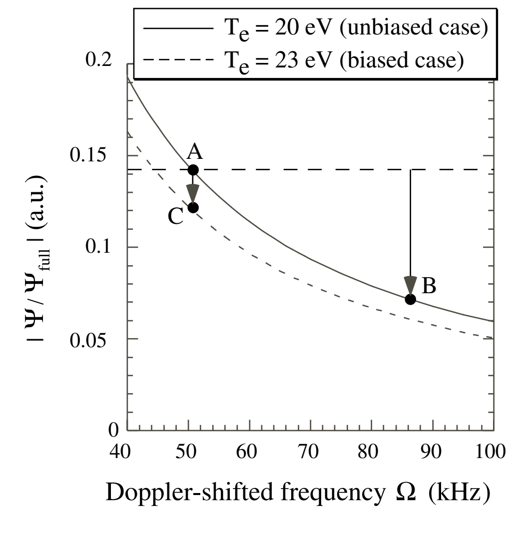

Fig. 6. Magnitudes of reconnection induced by resonant perturbation field in the cases of $T_{\mathrm{e}} = 20$ eV (—) and $T_{\mathrm{e}} = 23$ eV (- - -). The enhancement of Ω from A (48 kHz) to B (83 kHz) by the electrode biasing may strongly decrease the amount of the reconnection. The effect of the enhancement of Ω is about three times as large as that of increase in electron temperature from A to C induced by the electrode biasing.

where

$$\lambda(m = 6) = \frac{2\pi}{-r_{\mathrm{s}}\Delta'_{\mathrm{s}}}\frac{\Gamma(3/4)}{\Gamma(1/4)} = 0.224, \quad \mu_{\mathrm{c}} = \Omega\tau_{\mathrm{c}} \tag{2}$$

and Ψ_{full} is the amount of magnetic reconnection induced by resonant perturbation field in the absence of any current sheet at the resonance surface, and $\tau_{\mathrm{c}} = S^{3/5}\tau_{\mathrm{A}}$. Here, S and τ_{A} are Lundquist number and Alfvén transit time. The effect of the slight increase of electron temperature from 20 eV (unbiased case) to 23 eV (biased case) is examined as shown in Fig. 6 in which the magnitude of $\Psi/\Psi_{\mathrm{full}}$ is plotted against the Ω. It is found that the magnitude of $\Psi/\Psi_{\mathrm{full}}$ is decreased from A in unbiased case to B in biased one by the increase in Ω from 48 to 85 kHz. On the other hand, the increase of the electron temperature also gives a reduction in the magnitude of $\Psi/\Psi_{\mathrm{full}}$ from A in $T_{\mathrm{e}} = 20$ eV to C in $T_{\mathrm{e}} = 23$ eV, but it is only one-third that generated by the enhancement of Ω. Therefore, the influence of the slight increase of electron temperature is thought to be small compared with that of the enhancement of Ω in this experiment.

4. Summary

We have performed the detailed measurement of the penetration of RHF into tokamak plasmas on HYB-TOK-II. In comparison with the results of CSTN-IV, the large attenuation of B_{r1} has been found. In addition to this, a strong shielding of B_{r1} by changing the natural plasma rotation velocity by means of the electrode biasing has been shown. From these results it seems to conclude that even if electron temperature is very high such as TEXTOR-DED, both the screening current and the redistribution of plasma current due to the growth of the magnetic islands must be considered in the penetration process of RHF into tokamak plasma.

Acknowledgements

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References

[1] S. Takamura, H. Yamada, T. Okuda, Nucl. Fusion 28 (1988) 183.

[2] K.H. Finken, G.H. Wolf, Fusion Eng. Des. 37 (1997) 337.

[3] M. Kobayashi, T. Tuda, K. Tashiro, H. Kojima, K. Zhai, S. Takamura, Nucl. Fusion 40 (2000) 181.

[4] M. Kobayashi, H. Kojima, K. Zhai, S. Takamura, Phys. Plasmas 7 (2000) 3288.
[5] Y. Kikuchi, H. Kojima, T. Taniyama, M. Toyoda, Y. Uesugi, S. Takamura, Proceedings of 28th EPS Conference on Controlled Fusion and Plasma Physics, vol. 25A, Madeira, Funchal, Portugal, 2001, p. 277.
[6] K.H. Finken, T. Eich, A. Kaleck, Nucl. Fusion 38 (1998) 515.
[7] Y. Kikuchi, H. Kojima, T. Taniyama, M. Toyoda, Y. Uesugi, S. Takamura, Electr. Eng. Jpn. 139 (2002) 16.
[8] P.C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IOP, 2000, p. 79.
[9] R. Fitzpatrick, T.C. Hender, Phys. Fluids B 3 (1991) 644.