Dynamic Effects of Rotating Helical Magnetic Field on Tokamak Edge

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Abstract. Penetration processes of rotating helical magnetic perturbation (RHMP) into tokamak plasmas have been studied on a small tokamak device HYBTOK-II for dynamic ergodic divertor experiment preparing in TEXTOR. The penetration of RHMP has been discussed by using the measurements of RHMP in the plasma based on the growth of magnetic islands (i.e. tearing mode). In the case of the low Doppler-shifted frequency observed from the plasma, the amplification of RHMP in the plasma due to the spatial modification of plasma current has been found. A large Doppler-shifted frequency produces an expected attenuation of RHMP near the resonance surface due to flowing of screening current. A decrease of the amplification of RHMP originated from the suppression of the growth of magnetic islands has been also found by plasma current oscillation.

1. Introduction

The rotating helical magnetic perturbation (RHMP) with high poloidal mode numbers has a great potential on the control of tokamak edge plasma in terms of heat and particle exhaust, island formation, turbulent transport and core confinement. Especially, a mitigation of local heat deposition induced in static ergodic divertor, an efficient particle removal associated with a bent limiter and an enhanced confinement owing to plasma rotation shear are expected as main advantages. Therefore, dynamic ergodic divertor (DED) has been proposed as a project to realize such several possibilities [1]. The original pioneering work on the concept of DED was experimentally tested by our group using a small tokamak [2,3], in which a non-uniform wall loading was found to be ameliorated by a rotation of edge plasma structure. A periodic ion flux and an electron temperature modulation were observed near the wall.

Recently, new comprehensive studies [4-9] on DED have re-started by our group stimulated from the coming realization of the concept on TEXTOR (Lundquist number $S = 1.1\mathrm{x}10^5$) [10]. Penetration processes and dynamic behaviors of RHMP into the resonance layer in tokamak plasma have been investigated on CSTN-IV ($S \sim 250$) [4-6,9] as well as HYBTOK-II ($S = 2400 \sim 5000$) [8] small tokamaks. In this paper we describe the experimental results of the penetration processes of RHMP into tokamak plasmas on HYBTOK-II.

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 this experiment the plasma current and toroidal magnetic field were set to 5 kA and 0.28 T, respectively. The RHMP is created by two sets of local helical coils installed outside the

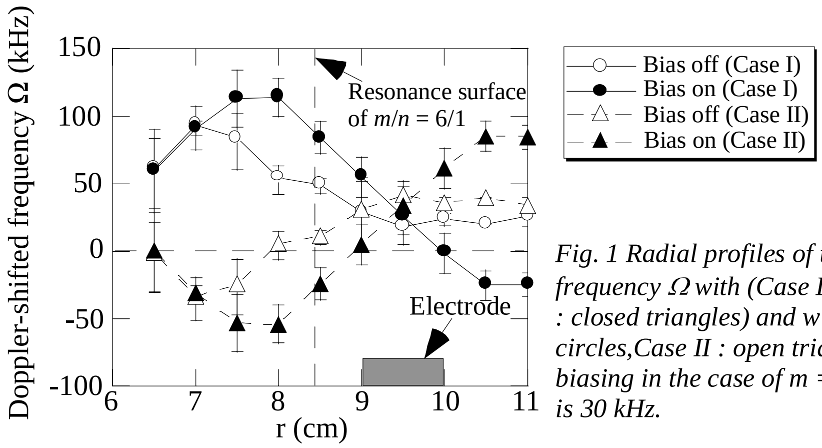

Fig. 1 Radial profiles of the Doppler-shifted frequency Ω with (Case I : closed circles, Case II : closed triangles) and without (Case I : open circles,Case II : open triangles) the electrode biasing in the case of m = 6. The driving frequency is 30 kHz.

vacuum vessel at eight toroidal sections among the 16 sections with the poloidal and toroidal mode numbers of m = 6 and n = 1. These two sets of coils are powered by IGBT inverter power supply with a phase difference of 90°. We can control the poloidal direction of RHMP by choosing either + or – 90°. Hereafter the terms “Case I” and “Case II” denote the rotation direction of RHMP, corresponding to the directions of ion and electron diamagnetic drift, respectively. In addition, a movable electrode made of titanium is inserted from the top of the vacuum vessel so as to change *E*x*B* drift velocity.

The radial profiles of RHMP and the poloidal magnetic 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 sections with and without the helical coils.

3. Penetration processes of RHMP into tokamak plasmas

3.1 Change of penetration due to local plasma rotation

From the experiment in CSTN-IV, it was found that the penetration process depends also sensitively on the relative poloidal rotation velocity between the tokamak plasma and RHMP. The relative velocity can be changed by either choosing the Case I or Case II, or applying an electrode biasing in HYBTOK-II. The plasma velocity was evaluated from the *E*x*B* drift velocity by using the following method. The plasma potential can be estimated from the fomula $V_p = V_f + 3T_e$ (in H_2 plasma), where V_p and V_f are the plasma potential and the floating potential, respectively. Using this relation, the radial electric field is obtained from the radial derivative of V_p. Hereafter Ω is used to refer to the relative velocity between the tokamak plasma and RHMP (i.e. Doppler-shifted frequency of RHMP).

Figure 1 shows the radial profiles of the Ω with and without the electrode biasing. 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. The radial profiles of B_{r1} at the section with the helical coils are shown in Fig. 2 which shows that the large Ω created by the electrode biasing enhances the *screening* of B_{r1} in the plasma. On the other hand, the *amplification* of B_{r1} in the plasma was observed in Case II as shown in Fig. 2(b). The enhancement of *amplification* of B_{r1} was observed with the electrode biasing in Case II. We can recognize from the *amplification* of B_{r1} around the resonance surface of m/n = 6/1 and 7/1 (sideband component) with the electrode biasing that the decrease of the Ω enhances the growth of magnetic islands of m = 6 and 7. Because a growth of magnetic

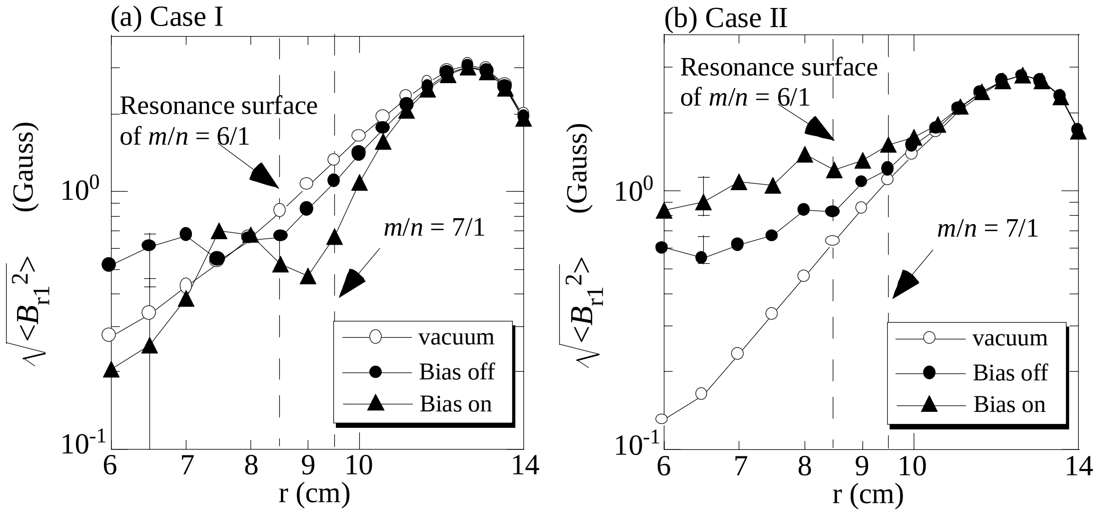

Fig. 2 Radial profiles of B_{r1} in vacuum (open circles) and in the plasma with (closed triangles) and without(closed circles) the electrode biasing. The directions of RHMP are set to (a) Case I and (b) Case II. The driving frequency is 30 kHz.

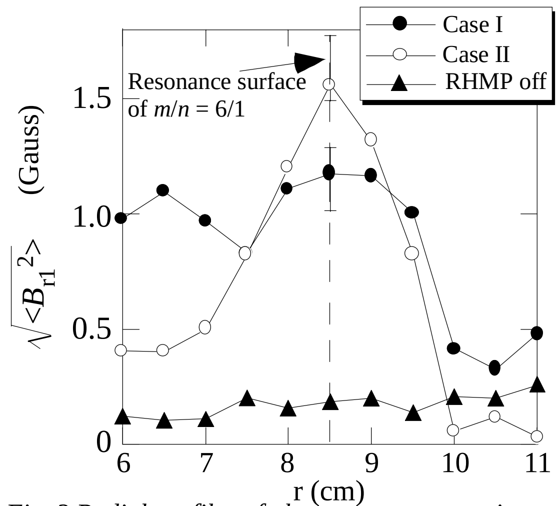

Fig. 3 Radial profiles of plasma response against the RHMP in Case I (closed circles) and Case II (open circles).Here, the closed triangles show the level of signal without RHMP. The driving frequency is 25 kHz.

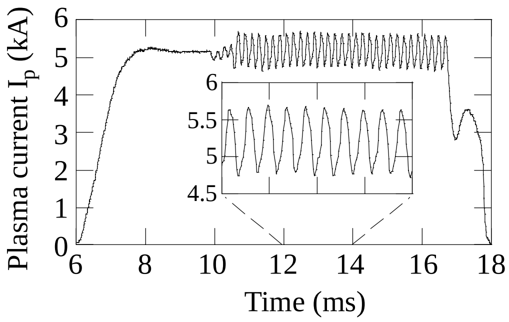

Fig. 4 Time evolution of plasma current with oscillation frequency of 5 kHz.

islands causes the *amplification* of B_{r1} in the resonance layer due to the spatial modification of plasma current [6].

Figure 3 indicates the radial profiles of B_{r1} at the section without the helical coils. Therefore, the B_{r1} shows us the plasma response against the RHMP directly, because the RHMP in vacuum is not detected there with magnetic probes. In the case of island formation (Case II), the B_{r1} has a maximum around the main resonance layer. It was also observed in another driving frequency. See Figs. 6 and 7. On the other hand, B_{r1} has a second maximum inside the main resonance, r < 8 cm under the condition of partial absorption (Case I). We suppose that the Alfven resonance ($\omega = k_{\parallel} v_A$), appearing at both sides of magnetic resonance ($\boldsymbol{k} \cdot \boldsymbol{B} = 0$), may contribute such a profile of B_{r1} [11,12].

3.2 Suppression of the growth of magnetic islands by plasma current oscillation

As mentioned above, magnetic islands are created by RHMP at the resonance surface.

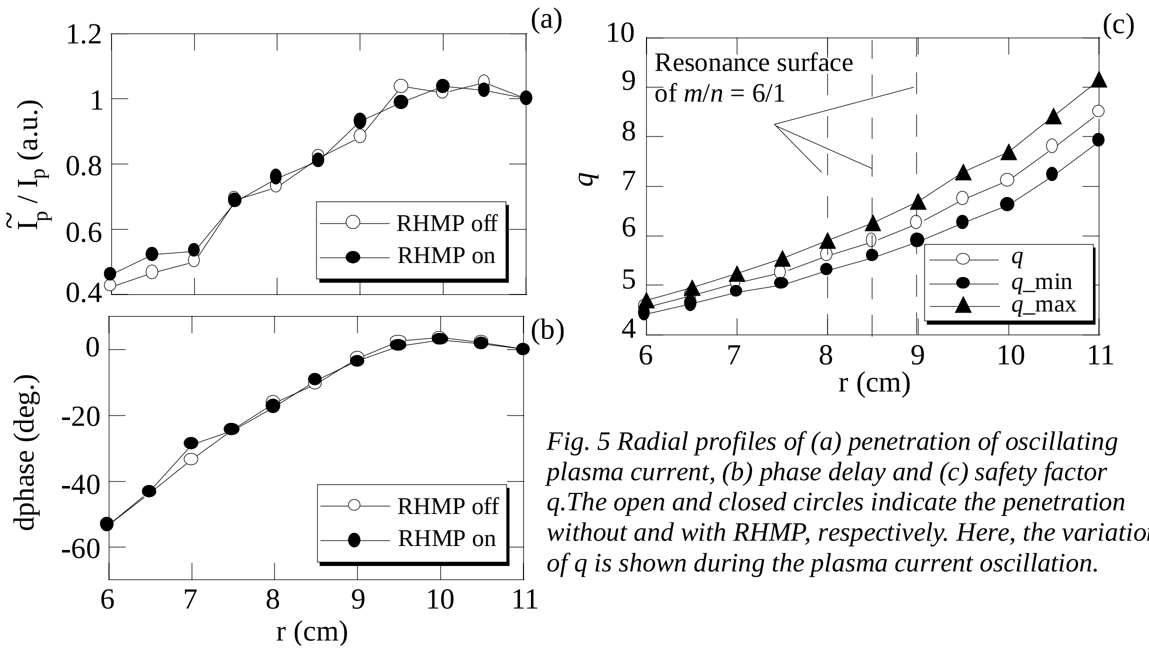

Fig. 5 Radial profiles of (a) penetration of oscillating plasma current, (b) phase delay and (c) safety factor q.The open and closed circles indicate the penetration without and with RHMP, respectively. Here, the variation of q is shown during the plasma current oscillation.

Therefore, we performed the DED experiment under the condition that the growth of magnetic islands is suppressed by plasma current oscillation. This idea comes from the experiment on HT-7 tokamak [13], in which the MHD activity (i.e. tearing mode instability) was suppressed by the plasma current oscillation because the position of resonance surface oscillates faster than the growth time of the magnetic islands.

Although the growth time of the magnetic islands is not so long (resulting from low electron temperature) in our experiment, the plasma current waveform can be controlled with a high-speed IGBT inverter power supply. Figure 4 shows the time evolution of the plasma current with oscillation frequency of 5 kHz. Under these conditions, we can measure the penetration of oscillating poloidal magnetic field by inserting the magnetic probe deeply inside the plasma as shown in Fig. 5. Fig. 5(c) indicates the change of the radial position of the resonance surface, and that its excursion distance (1 cm) is larger than the width of the magnetic island of m/n = 6/1 (0.7 cm) estimated by the vacuum field. It is also found that the RHMP does not give any large modification on the penetration of oscillating poloidal magnetic field. On the other hand, the oscillating period of the plasma current (100 μs) is the same order of the growth time of magnetic islands ($\gamma^{-1} = \tau_R^{3/5}\tau_A^{2/5} \sim 70$ μs, τ_R : resistive diffusion time, τ_A : Alfven transit time). Figures 6 and 7 indicate the radial profiles of B_{r1} at the sections with and without the helical coils, respectively. It was found that the *amplification* of B_{r1} in the plasma around the resonance surface is decreased by the plasma current oscillation. Therefore, it follows from these results that the growth of magnetic islands is suppressed by the plasma current oscillation.

4. Summary and discussion

We have discussed the penetration processes of RHMP into tokamak plasmas in terms of the growth of magnetic islands. Depending on the Doppler-shifted frequency of RHMP, the tearing modes are excited (*amplification* of B_{r1}) or damped (*screening* of B_{r1}). In addition, the amplification of B_{r1} was decreased when the suppression of the magnetic islands were induced by the plasma current oscillation.

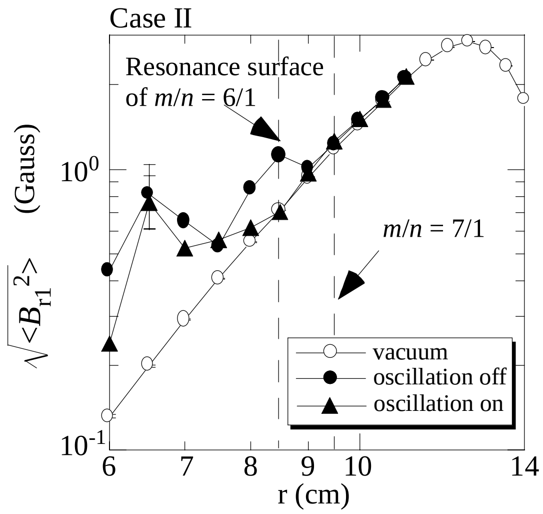

Fig. 6 Radial profiles of B_{r1} in vacuum (open circles) and in the plasma with (closed triangles) and without (closed circles) the plasma current oscillation. The driving frequency is 30 kHz.

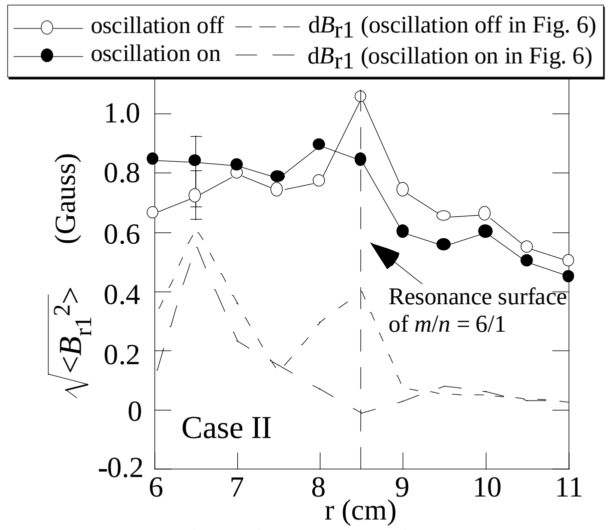

Fig. 7 Radial profiles of magnitude of plasma response against the RHMP with (closed circles) and without (open circles) the plasma current oscillation. The dashed lines indicate the differentials between the B_{r1} with and without the plasma. The driving frequency is 30 kHz.

On the other hand, the Alfven wave analyses of RHMP penetration, in which the helical coils are considered as an antenna, have been performed [11,12]. Their results show that the B_{r1} is screened outside the resonance surface, but the B_{r1} is amplified inside the resonance surface again. The similar behaviors in comparison with our experimental results have been found. In near future, we will compare the numerical analysis taking the effect of the plasma current gradient (i.e. tearing mode) for the Alfven wave propagation and absorption into account with those experimental results.

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