Penetration Process of the Externally Applied Rotating Helical Field into the Tokamak Plasma

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Introduction

Recently the TEXTOR group has proposed the concept of dynamic ergodic divertor (DED) [1] as one of the advanced tokamak scenarios. In the DED operation a rotating helical field is applied to induce the plasma rotation at the edge. The rotating frequency can be changed from dc to a few tens kilohertz depending on the required operational scheme.

On the other hand, the next step fusion device such as ITER-FEAT requires the high bootstrap current and high beta operation to achieve the long pulse discharge, and for good evidence for a future nuclear fusion reactor. However, such a highly advanced operation might create some new MHD activities, i.e., NTM and RWM. These modes are both related to the magnetic reconnection process at the resonance surface and the RWM stabilization is particularly found to be correlated with the plasma rotation [2]. In these contexts, the plasma response to the magnetic perturbation under the effect of plasma rotation becomes increasingly important.

In this paper we investigate the plasma response to the externally applied rotating helical field (RHF) with changing the rotating frequency of the RHF. We will discuss the plasma response to the external perturbation comparing the experiments with the linear analysis.

Experimental Setup

The compact research tokamak CSTN-IV [3] has the major radius of 0.4 m and minor radius of 0.1 m. The toroidal field is kept at 0.086 T in steady state. The RHF is induced with two sets of local helical coils (LHC) which create the (m, n) = (6, 1) mode perturbation. The coils are powered with rectangular ac voltage of 90 deg. phase difference in order to induce the traveling perturbation field. The radial and poloidal magnetic field on the midplane were measured using the small magnetic probes. From the q profile which was obtained by the measured poloidal field, the resonance surface for the (m, n) = (6, 1) mode is estimated at r = 7.5 cm. The amplitude of the RHF at the resonance surface is about 0.6 Gauss, which gives 6.7 mm as a saturated island width. The resistive MHD parameters in our device are as follows: the resistive diffusion time $\tau_R = \mu_0 a^2 / \eta \sim 350 \ \mu s$, the Alfvén transit time $\tau_A = Rq / V_A \sim 2.5 \mu s$, and Lundquist number $S = \tau_R / \tau_A \sim 140$. We have a relatively small Lundquist number due to the low temperature (~15eV) and also a small island growth time, which is a few microseconds.

Experimental Results

Figure 1 shows the plasma response to the RHF where the rotation speed of RHF is close to that of intrinsic plasma rotation, i.e., ExB drift which was deduced from the probe measurements. The plasma edge is at r = 10 cm, and the LHC's at 10.5 cm. Since the

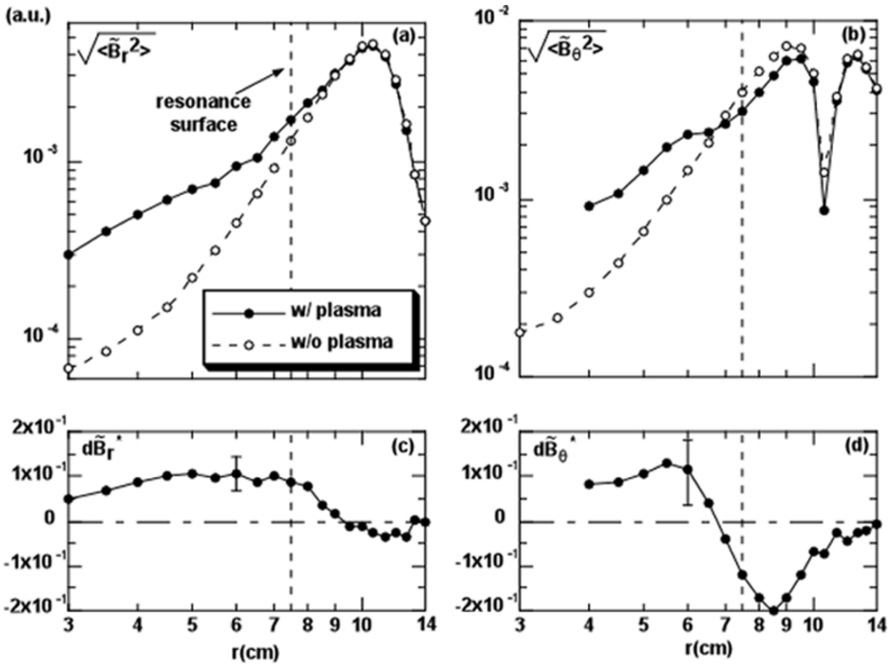

FIG.1 The radial profile of the perturbation field (a) B_r and (b) B_θ component with and without plasma. (c), (d) show the differentials in the perturbation between the cases with and without plasma, which are normalized by the vacuum field at r = 9 cm. The positive values mean the amplification in the plasma. In the case of Ω'~0. The typical error bars are indicated at r = 6 cm in (c) and (d).

Doppler-shifted frequency of the RHF (Ω') as seen from the frame of rotating plasma is close to zero, the reconnection at the resonance surface is expected to be large and there would appear a saturated island. It is observed that the B_r is amplified by 10% in the plasma almost all radial position while B_θ is attenuated by 20% around resonance surface and amplified at r < 6.5 cm by 10%. The response is different from the analysis discussed in ref. 1. Figure 2 shows the frequency dependence of the plasma response where the Ω' was increased from -10k to +15 kHz. It is found that as increasing the frequency the modification of the perturbation field, i.e., the amount of amplification in B_r and B_θ, and of attenuation in B_θ, becomes small. It is also noted that B_r is attenuated at r > r_s in the case of +15 kHz.

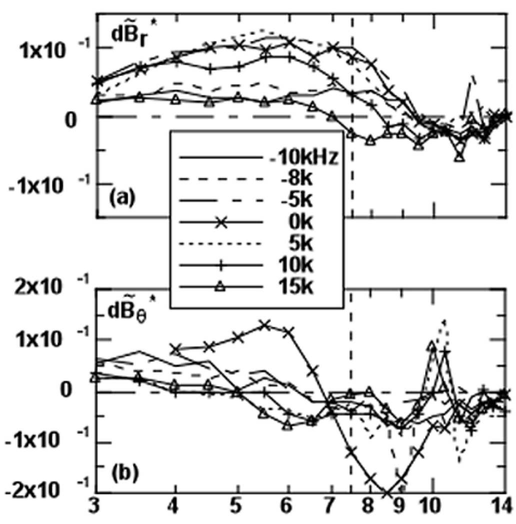

FIG.2 The differentials in the perturbations (a) B_r and (b) B_θ components between the cases with and without plasma. Ω' was changed from -10k to +15kHz. The positive values mean the amplification of RHF in the plasma.

Linear Analysis

It is assumed that the outer solution is always in equilibrium because the Alfvén transit time is much less than the period of RHF. The behaviour of single mode (m, n) perturbation field in the case of forced reconnection is described by the equation [4],

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\psi}{\partial r}\right)-\frac{m^2}{r^2}\psi-\frac{\partial j_z}{\partial r}\frac{\mu_0\psi}{B_\theta(1-qn/m)}=\mu_0 j_{coil}\delta(r-r_c) \qquad (1)$$

where j_{coil} and r_c are the current in the perturbation coil and its location, and δ is the delta function, respectively. Under the approximation that the plasma current is mostly concentrated inside the rational surface, we can write the stability index of the mode as [5],

$$\Delta' = \Delta'_0 + \Delta'_{coil}, \qquad (2)$$

where Δ' and Δ'_0 denote the total stability index and the index of natural mode, respectively. Because of the very low temperature in our device, the sheet current would diffuse across the island width rapidly. For this reason we approximate as

$$\partial\psi/\partial r\Big|_{r_s-0}^{r_s+0}\rightarrow 0, \quad i.e., \quad r_s\Delta'\rightarrow 0 \qquad (3)$$

at r = r_s, which gives the relation between the vacuum field Ψ_{vac} and the plasma response Ψ at r = r_s [5],

$$\Psi=\left(\frac{2m}{-r_s\Delta'_0}\right)\Psi_{vac}. \qquad (4)$$

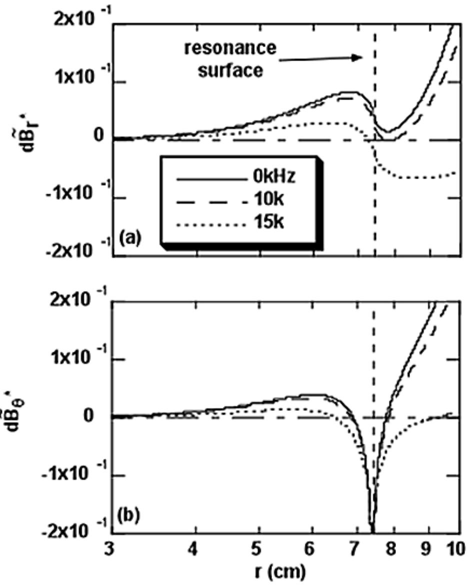

FIG.3 The linear analysis of the plasma response (a) dB_r and (b) dB_6 for various Ω'.

The frequency dependence of the plasma response should be taken into account through the reconnection process in the resistive layer since the outer solution is independent of the time derivative. The amount of reconnection at the resonance surface is obtained by the equation [6],

$$\frac{\Psi}{\Psi_{full}}=\frac{1}{1+e^{-i5\pi/8}\lambda(\Omega'\tau_c)^{5/4}}, \qquad (5)$$

here, $$\lambda=2\pi\Gamma(3/4)/(-r_s\Delta'_0\Gamma(1/4)) \qquad (6)$$

where Ψ_{full} is the amount of reconnected flux driven by the applied perturbation in the absence of any current sheet at r = rs, and $\tau_c\left(=S^{3/5}\tau_A\right)$ is the reconnection time scale of drift tearing mode, respectively. Combining Eqs. (4), (5), we obtain the frequency dependence of the plasma response at r = r_s,

$$\frac{\Psi}{\Psi_{vac}}=\left(\frac{2m}{-r_s\Delta'_0}\right)\frac{1}{1+e^{-i5\pi/8}\lambda(\Omega'\tau_c)^{5/4}}. \qquad (7)$$

We analyzed the natural mode stability using the measured q profile, and obtained the stability index $r_s \Delta'_0 = -9.71$, thus $\lambda = 0.22$.

Eq. (1) was solved under the boundary condition,

$$\lim_{r \to 0} \psi(r) = 0, \quad \psi(r_s + 0) = \psi(r_s - 0), \tag{8}$$

as well as Eq. (7). Figure 3 shows the modification $d\tilde{B}_r^*$ and $d\tilde{B}_\theta^*$ for various frequencies Ω'. Increasing the frequency reduces the amplification of $\tilde{B}_r$ and in the case of 15kHz the attenuation is observed at r > 7.5 cm. It is noted that the $\tilde{B}_r$ is still amplified at r < 7 cm even when it is attenuated around the resonance surface in 15kHz. As the frequency increases, the attenuation of $\tilde{B}_\theta$ around r = r_s and the amplification at r < 7 cm and r > 8 cm become small. Thus the amount of modification of the perturbation field decreases as increasing the frequency Ω'.

Discussion and Conclusion

As shown in Fig. 2, 3 we obtained a good agreement between experiments and the present linear analysis. It means that the plasma response observed in the present experiments is well described by the Eq. (1), i.e., the third term on the left hand side. One can find that the term represent the redistribution of plasma current due to the reconnection. In our experimental condition the reconnection time scale τ_c is very short because of the low temperature, which is estimated at 48 μs. Therefore the magnetic island has enough time to grow, and the current redistribution effect become dominant.

In the larger tokamak device such as TEXTOR, however, the inertia effect (in other words the skin effect around r = r_s) is no longer negligible. Considering the higher temperature case, the model should be developed by including the effect of both the current redistribution and the skin effect, as follows;

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\psi\right) - \frac{m^2}{r^2}\psi + \frac{1}{\delta_0^2 + v_{Apol}^2 / \Omega'^2}\psi$$
$$+ \frac{\mu_0}{(\delta_0^2 \Omega'^2 / v_{Apol}^2 + 1) B_\theta (r - r_s)} j_z \frac{d\psi}{dr} = \mu_0 j_{coil} \delta(r - r_c), \tag{9}$$

where δ_0 and v_{Apol} are the skin depth of the plasma and the poloidal Alfvén speed respectively, which is now under investigation.

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