Comparison of Rotation of Interchange Mode in Large Helical Device Plasmas with Various Ion Species*)

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(Received 28 December 2017 / Accepted 15 March 2018)

In order to clarify the mass effect and the atomic number effect on the rotation of the interchange MHD mode, the relationship between the mode rotation and the plasma rotation in hydrogen-rich plasmas is compared with that in helium-rich plasmas and deuterium-rich plasmas. In all cases, the frequency of the $m/n = 1/1$ resistive interchange mode is almost the same as the sum of the $\mathbf{E} \times \mathbf{B}$ rotational frequency and the electron diamagnetic rotational frequency at the $\iota/2\pi = 1$ resonant surface. This result indicates that the rotation of the resistive interchange mode does not depend on the ion species of which the plasma consists.

Keywords: MHD instability, interchange mode, mode frequency, plasma rotation, LHD

DOI: 10.1585/pfr.13.3402037

1. Introduction

The physical basis for the rotation of the resistive interchange mode, which is one of the key instabilities in helical plasmas, has been experimentally investigated in the Large Helical Device (LHD) [1]. In the previous study, the rotation of the peripheral mode, which is considered to be the resistive interchange mode [2], was compared with the plasma rotation. The mode frequency in the laboratory frame is almost consistent with the sum of the $\mathbf{E} \times \mathbf{B}$ rotational frequency and the electron diamagnetic rotational frequency at the resonant surface [3]. In order to compare these frequencies in the wide frequency region, $m/n = 1/1$ and 3/4 modes are analyzed as peripheral modes because the frequency of the $m/n = 1/1$ mode is fairly different from that of the $m/n = 3/4$ mode. Here, m and n are poloidal mode number and toroidal mode number, respectively. In addition, the rotation of the $m/n = 2/3$ resistive interchange mode in the edge region across the L-H transition has also been investigated [4]. In the L-phase and the H-phase, the mode frequency is almost consistent with the sum of the $\mathbf{E} \times \mathbf{B}$ rotational frequency and the electron diamagnetic rotational frequency at the resonant surface. After the transition to H-phase, the mode frequency rapidly decreases with a rapid reduction of the electron diamagnetic rotational frequency at the resonant surface because the electron density profile is changed considerably. These results suggest that the rotation of the resistive interchange mode might be decided by the $\mathbf{E} \times \mathbf{B}$ rotation and the electron diamagnetic rotation in hydrogen-rich (H-rich) plasmas produced by H gas puffing and the neutral beam injection (NBI) with a H beam. However, it is unclear whether the resistive interchange mode in the plasmas, where the dominant ion species is different from H, has the above characteristics. Therefore, in order to confirm that the characteristics are always observed, we investigate the relationships between the mode rotation and the combination of the $\mathbf{E} \times \mathbf{B}$ rotation with the electron diamagnetic rotation in plasmas, where the dominant ion species can vary.

In this study, the effect of the mass and the atomic number on the mode frequency of the resistive interchange mode are observed as the effects of the ion species. In the LHD, H, helium (He), and deuterium (D) gas can be used as the working gas. The mass of D is two times more than that of H, but the atomic number of D is the same as that of H. In the case of He, the mass is four times greater than that of H, and the atomic number is two times greater than that of H.

2. Experimental Setup

The resistive interchange modes are often observed at some resonant surfaces in the LHD. In this study, only the $m/n = 1/1$ mode is analyzed because the $m/n = 1/1$ mode is observed in various experimental conditions. The amplitude and the frequency of the $m/n = 1/1$ mode is evaluated from the poloidal magnetic fluctuation, which is measured by a magnetic probe [5]. The $\mathbf{E} \times \mathbf{B}$ rotational frequency is obtained by Charge eXchange Spectroscopy (CXS) measurement [6], which requires the perpendicular NBI. The electron and the ion diamagnetic rotational frequencies are

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*) This article is based on the presentation at the 26th International Toki Conference (ITC26).

Table 1 Experimental conditions of each plasma discharge.

Plasma	Beam species		Puffing gas
	tangential NBI	perpendicular NBI	
H-rich	H	H	H
He-rich	H	H	He
D-rich	H	D	D

obtained by the CXS measurement system and the YAG laser Thomson scattering system [7]. The $m/n = 1/1$ resistive interchange mode is localized at the $\iota/2\pi = 1$ resonant surface. The resonant surface is obtained from an equilibrium decided by the equilibrium mapping technique [8]. The magnetic configuration and plasma parameters are similar to those in previous work for H-rich plasmas [3]. The magnetic configuration is set such that the absolute value of the toroidal magnetic field $|B_t| = 1.375$ T, vacuum magnetic axis position $R_{ax} = 3.60$ m, and aspect ratio $A_p = 5.7$. The volume-averaged beta value is ~1 % and the plasma current is less than 25 kA/T. The effect of the above beta value and plasma current on the stability of the resistive interchange mode is small. Each plasma is produced by electron cyclotron heating (ECH) and is then maintained by the tangential and the perpendicular NBI. H is the beam species of the tangential NBI in each plasma. In case of the perpendicular NBI, the beam species is H in H-rich and He-rich plasmas, but is D in D-rich plasmas. The power of the perpendicular NBI is modulated for CXS measurement during discharges. In D-rich plasmas, modulated ECH is also applied during a discharge. In H-rich, He-rich, and D-rich plasmas, H, He, and D gas puffing is used, respectively. The experimental conditions of these discharges are summarized in Table 1.

3. Experimental Results

Figure 1 shows a waveform of typical discharges where the resistive interchange mode appears in H-rich, He-rich, and D-rich plasmas. Figures 1 (a), 1 (h), and 1 (o) show the tangential NBI power. The perpendicular NBs are also injected for CXS measurement, and their total power is ~4 MW. The volume-averaged beta value is almost the same [Figs. 1 (b), 1 (i), and 1 (p)], but the line-averaged electron density of the D-rich plasma is larger than that of H-rich and He-rich plasmas, as shown in Figs. 1 (c), 1 (j), and 1 (q). The density ratio of H to He, $n_H/(n_H + n_{He})$, is ~0.9 in the H-rich and the D-rich plasma, and ~0.5 in the He-rich plasma as shown in Figs. 1 (d), 1 (k), and 1 (r). The density ratio of D to H, $n_D/(n_H + n_D)$, of the H-rich and the He-rich plasma is zero. On the other hand, $n_D/(n_H + n_D)$ of the D-rich plasma is estimated to be greater than 0.65 because this ratio is ~0.65 in other D-rich plasma discharges with the same magnetic configuration but the lower electron density (~0.5×10^{19} m^{-3}) than that of the discharge in Figs. 1 (h) - (n). In Figs. 1 (f), 1 (g), 1 (m), 1 (n), 1 (t), and 1 (u), the positive (negative) sign in the vertical axis corresponds to the ion (electron) diamagnetic direction. The amplitude of the $m/n = 1/1$ mode in the H-rich and the He-rich plasma is larger than that in the D-rich plasma as shown in Figs. 1 (e), 1 (l), and 1 (s). This is because, in the case of the H-rich and the He-rich plasma, the pressure gradient at the $\iota/2\pi = 1$ resonant surface, which is proportional to the electron diamagnetic rotation frequency as shown in Figs. 1 (g), 1 (n), and 1 (u), is larger than that in the D-rich plasma. In all cases, the $m/n = 1/1$ mode rotates in the electron diamagnetic direction in the laboratory frame as shown in Figs. 1 (f), 1 (m), and 1 (t). When the mode rotation is compared with the plasma rotation, the mode frequency is close to the sum of the $\mathbf{E} \times \mathbf{B}$ rotational frequency and the electron diamagnetic rotational frequency, $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$, rather than the sum of the $\mathbf{E} \times \mathbf{B}$ rotational frequency and the ion diamagnetic rotational frequency, $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{idia}}$. In addition, the mode frequency is almost constant even if $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ is varied quickly. On the other hand, the moving-averaged $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ is almost the same as the mode frequency. This result shows that the mode frequency is decided by the averaged $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ rather than $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ itself. These relationships are a common characteristic in H-rich, He-rich, and D-rich plasmas, which suggests that the rotation of the resistive interchange mode does not depend on the ion species. Moreover, at the $\iota/2\pi = 1$ resonant surface, the electron diamagnetic frequency is larger than the $\mathbf{E} \times \mathbf{B}$ rotational frequency in all cases. This result suggests that the pressure profile plays a significant role in the rotation of the $m/n = 1/1$ resistive interchange mode.

Figure 2 shows radial profiles of some rotational frequencies in the H-rich plasma corresponding to Figs. 1 (a) - (g). In the core region including the $\iota/2\pi = 1$ resonant surface, the $\mathbf{E} \times \mathbf{B}$ rotational frequency is almost zero. Therefore, the electron diamagnetic rotational frequency is dominant at the resonant surface of the $m/n = 1/1$ mode. However, in case of edge modes such as $m/n = 3/4$ and 2/3, not only the electron diamagnetic rotational frequency but also the $\mathbf{E} \times \mathbf{B}$ rotational frequency might be important because the $\mathbf{E} \times \mathbf{B}$ rotational frequencies at the $m/n = 3/4$ and 2/3 resonant surface are larger.

In this study, the relationship between the rotation of the $m/n = 1/1$ mode and the plasma rotation in H-rich plasmas is compared with that in He-rich and D-rich plasmas, in order to clarify the physical mechanism for the resulting rotation of the resistive interchange mode in the plasmas where the dominant ion species is different. In all cases, the $m/n = 1/1$ mode rotates in the electron diamagnetic direction in the laboratory frame, and the mode frequency is almost the same as the $\mathbf{E} \times \mathbf{B}$ rotational frequency adding to the electron diamagnetic rotational frequency at the $\iota/2\pi = 1$ resonant surface. This result suggests that the rotation of the resistive interchange mode does not depend on the ion species.

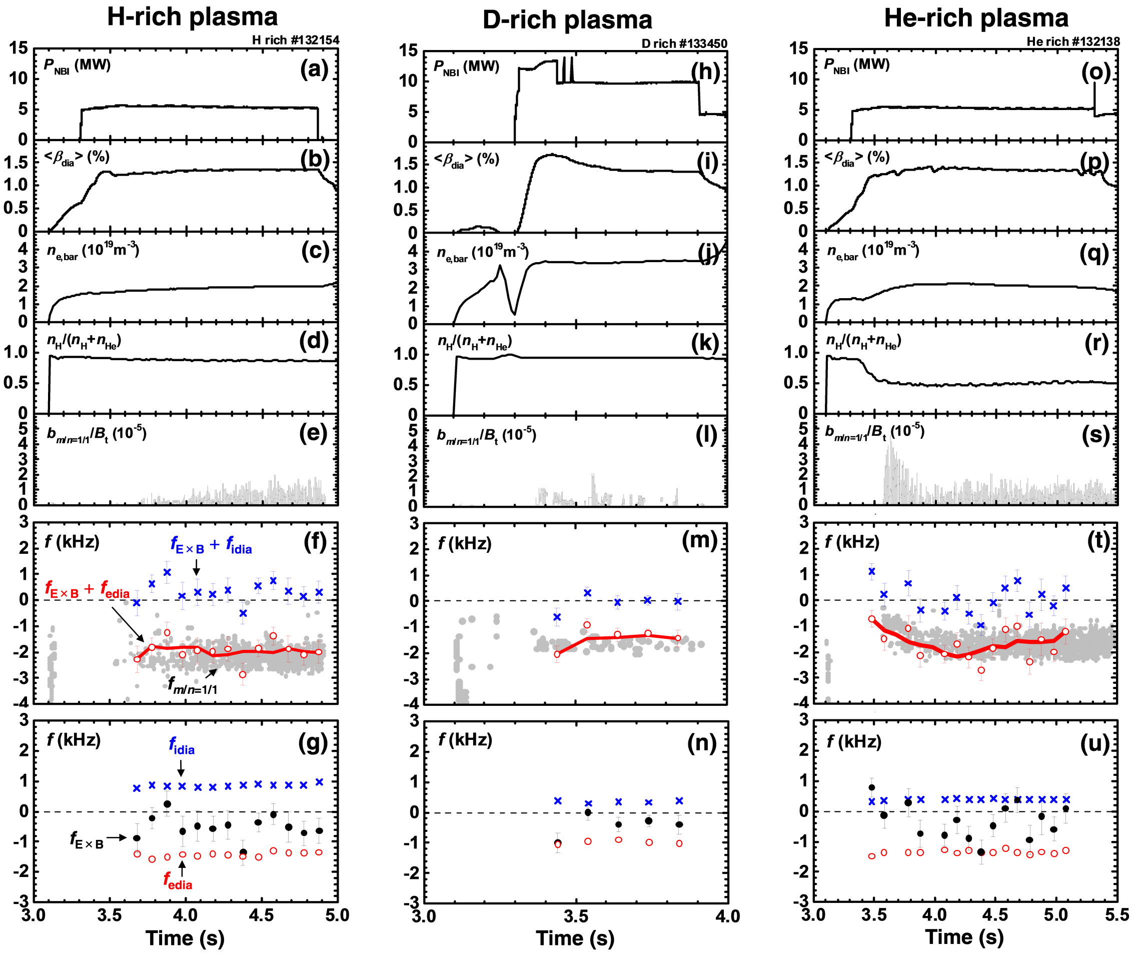

Fig. 1 Time evolution of (a) tangential NBI power; (b) volume-averaged beta value; (c) line-averaged electron density; (d) density ratio of H to He; (e) amplitude of the $m/n = 1/1$ mode; (f) frequency of the $m/n = 1/1$ mode, $f_{m/n=1/1}$ (closed circles), $\mathbf{E} \times \mathbf{B}$ rotational frequency adding to ion diamagnetic frequency, $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{idia}}$ (crosses), adding to electron diamagnetic frequency, $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ (open circles), and moving-averaged $f_{\mathbf{E}\times\mathbf{B}} + f_{\mathrm{edia}}$ (line); and (g) $\mathbf{E} \times \mathbf{B}$ rotational frequency (closed circles), ion diamagnetic rotational frequency (crosses), and electron diamagnetic rotational frequency (open circles) in the H-rich plasma. (h) - (n) Same parameters as (a) - (g) in the D-rich plasma. (o) - (u) Same parameters as (a) - (g) in the He-rich plasma. The positive (negative) sign corresponds to the ion (electron) diamagnetic direction in (f), (g), (m), (n), (t), and (u).

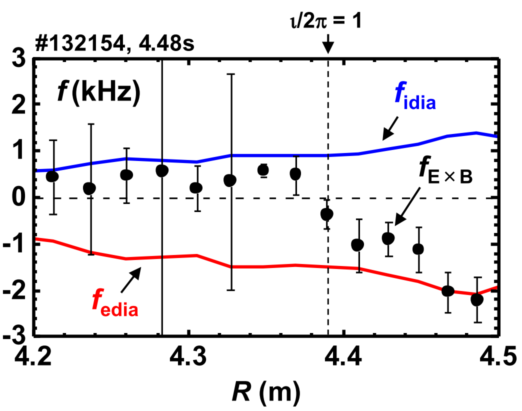

Fig. 2 Radial profiles of the $\mathbf{E} \times \mathbf{B}$ rotational frequency (closed circles), the ion diamagnetic rotational frequency (blue), and the electron diamagnetic rotational frequency (red) in the H-rich plasma as shown in Figs. 1 (a) - (g). The vertical dashed line indicates the $\iota/2\pi = 1$ resonant surface.

In this paper, the radial location of the $m/n = 1/1$ mode is decided by the equilibrium mapping technique [8]. On the other hand, the radial location of the resonant surface can be directly measured using ECE measurement, which is radially local fluctuation measurement, installed in the LHD. However, in discharges with the low absolute value of the toroidal magnetic field (low $|B_t|$), such as these discharges with $|B_t|$ of 1.375 T as shown in Fig. 1, the sensitive region of ECE measurement is outside the resonant surface. $|B_t|$ should be larger (e.g., 1.5 T) so that ECE measurement can directly identify the resonant surface.

In recent years, theoretical studies on the effect of plasma flow on MHD instabilities are also actively conducted, but in order to study the physical mechanism of this effect, it is necessary to construct an MHD model including the two fluid effect. It is expected that the simulation of experiment results about ion species dependence of MHD modes like this study is useful to confirm the validity of MHD instability codes including the two fluid effect.

Acknowledgments

This work was supported by NIFS under contracts ULPP042. The authors are grateful to the LHD operation group for their excellent technical support.

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