Experimental observation of hysteresis of magnetic island dynamics during change of poloidal flow in a helical plasma

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1. Introduction

Magnetic islands play key roles in toroidal plasma confinement from the viewpoint of MHD stability. In Tokamaks, for example, a seed island triggers a neoclassical tearing mode, and its growth leads to serious deterioration of the confinement. On the other hand, in a helical device, magnetic islands intrinsically disappear as they are stabilized during a plasma discharge under certain conditions [1, 2]. The nonlinear growth or suppression of the magnetic island during a discharge has been observed in the Large Helical Device (LHD) [1]. The resonant magnetic perturbation (RMP) coils make a vacuum magnetic island with $m/n =$ 1/1 (here, m/n is poloidal/toroidal Fourier mode number) structure. Both magnetic island growth and suppression is seen with the two disparate plasma responses distinguished by a sharp boundary in the parameter space defined by the plasma β and collisionality at the rational surface (Fig.1). Generally, at low beta (β) and high collisionality (ν), the plasma tends to make the island grow in width. However at sufficiently high β and/or low ν, the plasma abruptly changes to a configuration with no island. Recently, the causal relations between the island dynamics and the plasma rotation attract attention experimentally [3] and/or theoretically [4, 5]. Experimental results showing that the poloidal rotation ω_{pol} increases prior to the island
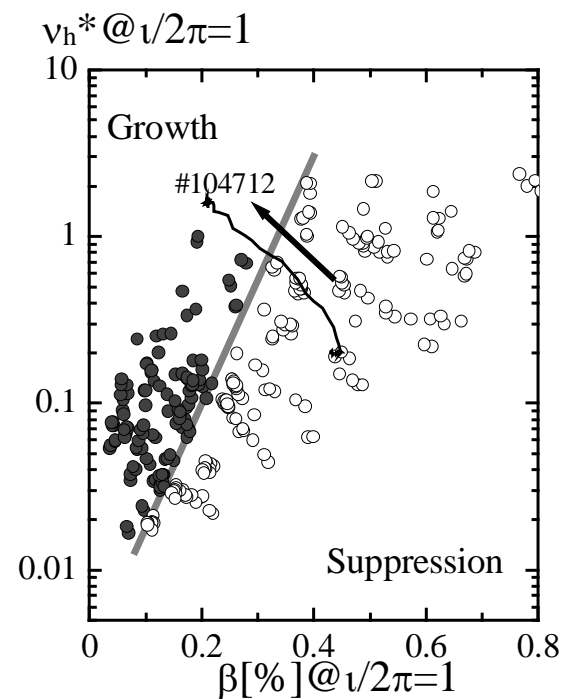

Fig.1 Island growing (filled) and suppressing (closed) region in β - ν space. Boundary is drawn by grey solid line. Black solid line indicates trajectory of typical single discharge

suppression regardless of its direction have been observed in LHD and TJ-II [3]. Theoretical studies have addressed this problem, in which the viscous torque and electromagnetic torque have key roles to explain the above phenomena in helical plasmas. The purpose of this study is to clarify the dynamics of the poloidal rotation during the island transition and its hysteresis.

2. Dynamic behaviour of magnetic island

To clarify the dynamic behaviour of the magnetic island when crossing the boundary from the region of suppression to the region of growth, the heating power of the neutral beam (NB) is controlled in a single discharge to change β and ν. The black solid line intersecting the grey solid line in figure 1 is a typical trajectory of such a plasma. Figure 2 shows typical waveforms when the magnetic island transits from suppression to growth. The balanced co- and counter- tangential NBs are injected for keeping the normalized plasma current I_p/B_t less than 10kA/T to avoid a change of the magnetic shear due to the modification of the rotational transform $(\iota/2\pi)$ profile. An additional perpendicular NB also has a
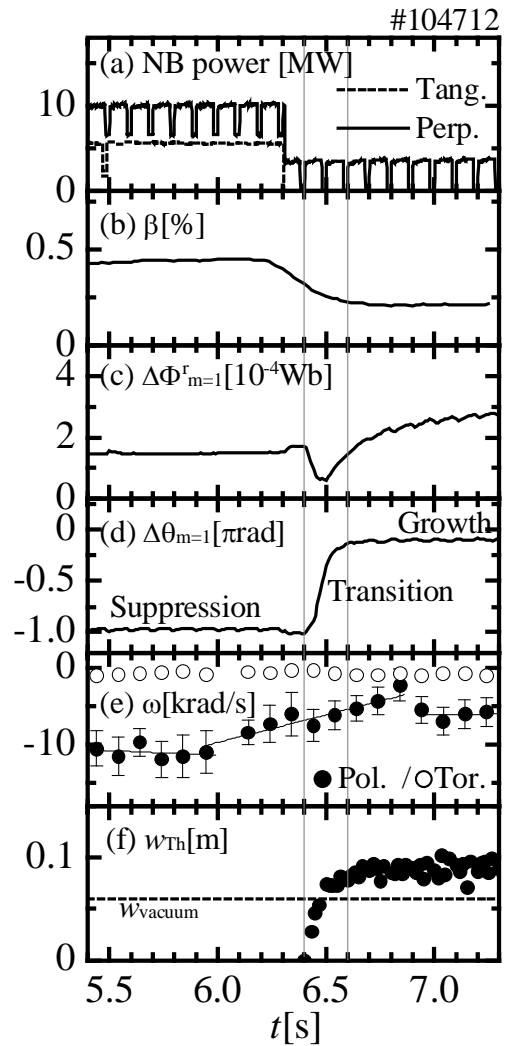
Fig.2 Time evolution of (a) Tangential (dashed) and perpendicular (solid) NB's port through power, (b) β at rational surface, (c) plasma response "field", (d) phase difference, (e) Poloidal (filled) and toroidal (open) plasma rotation and (f) island width estimated from T_e profile

role of a diagnostic beam for CXS to measure the plasma rotation. The $\Delta\Phi^r_{m=1}$ is defined as the amplitude of an $m = 1$ component of the plasma response field (fig.2 (c)). The phase difference ($\Delta\theta_{m=1}$) is defined as the difference of the phase between the plasma response and the RMP (fig.2 (d)). When the phase difference is zero ($\Delta\theta_{m=1} = 0$), the magnetic island grows, when it is out of phase ($\Delta\theta_{m=1} = \pi$), the magnetic island is suppressed. As for the plasma flow at just outside the $\iota/2\pi = 1$, the toroidal rotation, ω_{tor}, (open in fig.2 (e)) is much smaller than the poloidal one, ω_{pol}, (closed in fig.2 (e)) throughout the discharge. Before $t = 6.4$s, the width, w_{Th}, of the local flattening of the electron temperature profile measured by Thomson scattering does not appear. The phase difference of $\Delta\theta_{m=1} = -\pi$ means island suppression. In

the period of $6.4s < t < 6.6s$, the phase difference shifts from $\Delta\theta_{m=1} = -\pi rad$ (anti-phase) to $-0.1\pi rad$ (in-phase) and w_{Th} exceeds the vacuum width w_{vac}. The island width saturates since $t = 6.6s$ (fig.2 (f)). The behaviour of the poloidal rotation shows that the $|\omega_{pol}|$ decreases at $t = 6.1s$ prior to the transition (around $t = 6.4s$) whereas the ω_{tor} does not change.

Figure 3 shows the relationship between the phase shift, $\Delta\theta_{m=1}$, and the poloidal rotation, ω_{pol}, in which arrows indicate the time trend. In the case of the transition from growth to suppression (fig.3 (a)) the phase shift $\Delta\theta_{m=1}$ transits from $\Delta\theta_{m=1} \sim -0.1\pi rad$ to $\Delta\theta_{m=1} \sim -\pi rad$. The threshold value of the poloidal rotation, ω_{pol}^{th}, derived from the fitting of a Heaviside-function is $\omega_{pol}^{th} = -9.0 krad/s$. In the other case of the transition from suppression to growth (fig.3 (b)) $\omega_{pol}^{th} = -6.6 krad/s$. These experimental observations imply that when the magnetic island is suppressed by the poloidal rotation once, the suppression lasts until the poloidal rotation becomes small enough. And it is an advantageous behaviour from the viewpoint of the magnetic island stabilization.

Fig.3 Relationship between $\Delta\theta_{m=1}$ and ω_{pol}. Case of (a) growth to suppression, (b) suppression to growth. Arrows indicate time trend. Grey solid line indicates threshold of poloidal rotation for transition (ω_{pol}^{th}). Threshold values of poloidal rotation are (a) $\omega_{pol}^{th} = -9.0 krad/s$ and (b) $\omega_{pol}^{th} = -6.6 krad/s$, respectively

3. Discussion

The dynamics of the magnetic island are affected by the poloidal rotation that changes during the island transition while the toroidal rotation does not change so much. In this study, the balanced injected NBI causes a toroidal rotation that is smaller than the poloidal rotation. Therefore, the effect of the toroidal rotation on the island dynamics is not discussed here. To explain the island dynamics, one candidate is the relationship between the poloidal viscous drag force and the magnetic torque [4, 5]. Due to the increase of the poloidal flow, the viscous drag force overcomes the magnetic torque between the externally imposed field and some kind of current structure with $m/n = 1/1$, which causes the current structure to be shifted
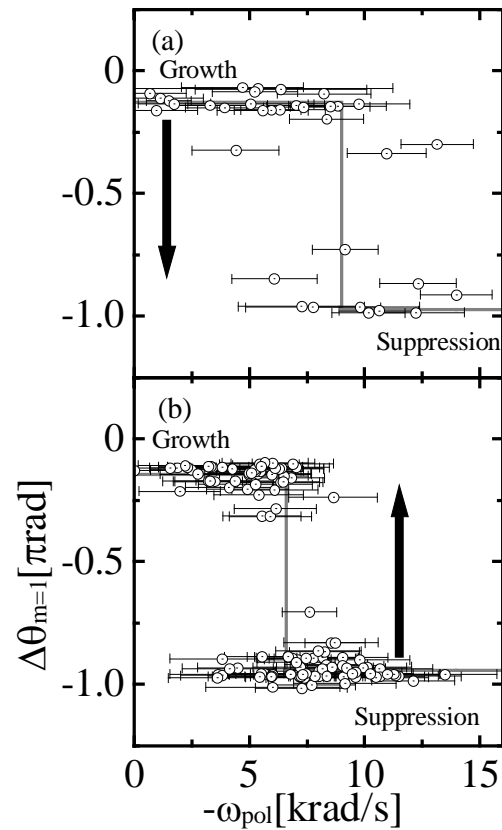
(rotated) to suppress the magnetic island and vice versa. In the above situation, the hysteresis is predicted by theoretical study. Nishimura et al. [4] has shown that the relationship between the island width and the vacuum one has a hysteresis, in which the thresholds of the vacuum island width are different in each transition. Hegna [5] has provided a theoretical prediction consistent with the experimental observations: When the island experiences a transition from suppression to growth, the threshold value of the poloidal rotation is smaller than the rotation value in the reverse transition. These theories [4,5] are based on a balance of electromagnetic and viscous torques at the rational surface. Further progress of theoretical studies is expected to explain that phenomena.

4. Summary

In the LHD experiment, the poloidal flow in the electron-diamagnetic direction outside the rational surface increases or decreases prior to the transition of the magnetic island. These experimental observations clarify the fact that a significant poloidal flow affects the magnetic island dynamics. It is thought that due to the increase of the poloidal flow, the viscous drag force overcomes the magnetic torque between the externally imposed field and some kind of current structure with $m/n = 1/1$. Hysteresis is observed experimentally. These experimental observations imply that when the magnetic island is suppressed by the poloidal rotation once, the suppression lasts until the poloidal rotation becomes small enough. And it is an advantageous behaviour from the viewpoint of the magnetic island stabilization.

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