Response of magnetic island to resonant magnetic perturbation in LHD

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1. Introduction

The behaviors of magnetic islands in helical plasmas are important due their impact on MHD stability and confinement. In helical plasmas such as LHD and TJ-II, it has been reported that the magnetic islands show spontaneous behavior of growth/healing during the discharge \cite{1}. In the LHD experiment, the saturated island states can be clearly divided into two regions in the space of plasma beta $\beta$ and collisionality $\nu$ \cite{2}. Under the magnetic configuration with vacuum magnetic island produced by the static resonant magnetic perturbation (RMP) with $m/n=1/1$ (Here, $m/n$ is poloidal/toroidal Fourier mode number.), the plasma tends to make the island grow (be healed) in width at low (high) $\beta$ and high (low) $\nu$ as shown in figure 1. While $\beta$ and $\nu$ can directly affect island physics through Pfirsch-Schluter and bootstrap current effects, efforts to understand these results via these mechanisms failed \cite{1}. Rather, it has been suggested that plasma flow physics can explain the observations \cite{4, 5}. Understanding magnetic island physics can lead to plasma control techniques that can ultimately prove beneficial to plasma confinement and stability.

2. Island dynamics with static RMP

In recent experiments, it was found that the poloidal rotation driven by the neoclassical radial electric field affects the island transition (growth / healing) in TJ-II and LHD \cite{1}. The poloidal rotation is observed to change prior to both island healing and regrowth with the threshold value for the poloidal rotation differing. Figure 2 shows the relationship between the phase difference,
$\Delta \theta_{m=1}$ and the poloidal rotation, in which the time evolution is shown by the arrow. Here, $\Delta \theta_{m=1}$ is defined as the difference of the phase between the plasma response and the RMP. The magnetic island grows (is healed) for $\Delta \theta_{m=1} = 0$ ($\pi$ rad). In the healing case, the plasma response provides a magnetic field that exactly cancels the vacuum field at the rational surface. The absolute value of the poloidal rotation for island suppression (9.0 krad/s) is larger than that for island growth (6.6 krad/s) as shown in figure 2. Furthermore, the experimental observation showing the hysteresis with respect to $\beta$ was obtained as shown in figure 3 [3]. The magnetic island grows ($\Delta \theta_{m=1} = 0$) in the beginning of the discharge. When the $\beta$ increases, the $\Delta \theta_{m=1}$ maintains $\sim 0$ until $\beta = 0.25\%$. After that, $\Delta \theta_{m=1}$ goes to $\Delta \theta_{m=1} = -\pi$ (rad) while the $\beta$ increases. Finally island is healed ($\Delta \theta_{m=1} = -\pi$ rad) at $\beta = 0.3\%$.

On the other hand, $\Delta \theta_{m=1}$ goes back to $\Delta \theta_{m=1} = 0$ at $\beta = 0.1\%$ and the magnetic island regrows. Similar to the case for the poloidal rotation, when the frequencies for healing and grow did not coincide, $\beta$ for island suppression is larger than that for island growth.

These experimental results show the existence of a hysteresis in the magnetic island transition dynamics. Through those studies, we have clarified the plasma parameter effects on magnetic island under the static RMP.

### 3. Plasma response with time-varying RMP

The above mentioned experimental facts are obtained with the static RMP. If plasma parameters are fixed and RMP is changed, the plasma response to RMP can be clarified. Figure 4 shows two cases of discharges with time-varying RMP; plasma $\beta$ and $v$ are almost constant in both cases. The
time-varying RMP does not drive the ohmic plasma current because it has no toroidal component. In the beginning of the case of increasing RMP (Fig.4 left), magnetic island is healed until \( t = 7 \)s. From the local flattening size of \( T_e \) profile, the island width \( (w) \) cannot be determined (Fig.4 left (f)). The amplitude of the plasma response field \( \Delta \Phi_{plm=1} \) (unit of [Wb] detected by non-planar flux loops) indicates the same value of that of external field (RMP) \( \Delta \Phi_{extm=1} \) (converted to an equivalent value at the flux loops). When the RMP exceeds a critical value, the island suddenly appears at \( t = 7 \)s. Its width \( (w) \) becomes larger than that of the vacuum island \( (w_{vac}) \) as indicated by the dashed line. At the time of transition from healing to growth, the phase shift \( \Delta \theta_{m=1} \) shows the rotation from \( \Delta \theta_{m=1} = -\pi \) rad to \( \Delta \theta_{m=1} = 0 \) in the ion diamagnetic direction. On the other hand, for decreasing RMP (Fig.4 right), \( w \) remains larger than \( w_{vac} \) even if the RMP falls to almost zero. The difference between \( w \) and \( w_{vac} \) gradually goes up with time because the \( \Delta \Phi_{plm=1} \) is almost constant whereas the \( \Delta \Phi_{extm=1} \) decreases through the discharge. From these experimental results, the clear hysteresis is also observed as shown in Fig. 5. In the case of increasing RMP amplitude (open circles), the \( w_{vac} \) also goes up with time. The magnetic island is healed until \( w_{vac} = 70 \) (mm). Beyond that, island width \( w \) increases and exceeds \( w_{vac} \). On the other hand, in case a decreasing RMP amplitude (closed circles), \( w \) linearly goes down with \( w_{vac} \) but its width does not fall below \( w_{vac} \). As is the case with static RMP, hysteresis is observed in the time-varying RMP case. In fact, in this case we have never observed island healing despite of making very small the RMP.

4. Discussion and Summary

The mechanisms of island healing and growth have been investigated. The former is thought to be due to poloidal rotation shielding of the RMP. However, the physical mechanism associated with island growth has not yet been clarified. Theoretical models [4-6] based on the
balance of electromagnetic and viscous torques at the rational surface have been approached to explain those experimental results. The healing of islands by plasma flows is also observed in reduced fluid simulations [6]. In particular, the relation of the critical beta ($\beta_{\text{crit}}^{\text{growth}}$ for growth and $\beta_{\text{crit}}^{\text{heal}}$ for healing) is described in detail in Ref.[4] as follows

$$\beta_{\text{crit}}^{\text{growth}} \approx \beta_{\text{crit}}^{\text{heal}} \sqrt{\frac{2}{|\omega_0'|\tau_L}} \quad (1)$$

under the condition of $\omega_0'|\tau_L >> 1$, where $|\omega_0'|$ denotes the difference between natural frequency (determined by neoclassical transport and external sources) and electron diamagnetic frequency and $\tau_L$ is a function of Lundquist number, perpendicular collisionality and Alfvén frequency. The experimental observation is consistent with the theoretical prediction of the magnitude relation ($\beta_{\text{crit}}^{\text{growth}} < \beta_{\text{crit}}^{\text{heal}}$). The healing of islands by plasma flows is also observed in reduced fluid simulations [6, 7]. It is also pointed out that the critical value of RMP might be strongly affected in the presence of the curvature driven tearing mode [6, 7], which might be able to explain that $w$ becomes larger than $w_{\text{vac}}$ when the island grows. These results help to clarify the physical mechanisms of growth and healing of islands in helical for a comprehensive understanding of the dynamics of magnetic islands.

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**References**