Response of magnetic island to resonant magnetic perturbation in LHD

Y. Narushima[1], S. Sakakibara[1], F. Castejón[2], K. Y. Watanabe[1], M. Yoshinuma[1], H. Funaba[1], S. Ohdachi[1], Y. Suzuki[1], S. Nishimura[1], T. Estrada[2], F. Medina[2], D. Lopez-Bruna[2], M. Yokoyama[1], K. Ida[1], C. C. Hegna[3], LHD Experiment Group[1] and TJ-II Experiment Group[2]

[1] *National Institute for Fusion Science, Toki 509-8292, Japan*

[2] *Laboratorio Nacional de Fusión. CIEMAT, Avenida Complutense 22, 28040 Madrid, Spain*

[3] *University of Wisconsin-Madison, 1220 Linden Dr. Madison, WI 53706-1557 United States*

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 [1]. In the LHD experiment, the saturated island states can be clearly divided into two regions in the space of plasma beta β and collisionality ν [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) β and high (low) ν as shown in figure 1. While β and ν can directly affect island physics through Pfirsch-Schluter and bootstrap current effects, efforts to understand these results via these mechanisms failed [1]. Rather, it has been suggested that plasma flow physics can explain the observations [4, 5]. Understanding magnetic island physics can lead to plasma control techniques that can ultimately prove beneficial to plasma confinement and stability.

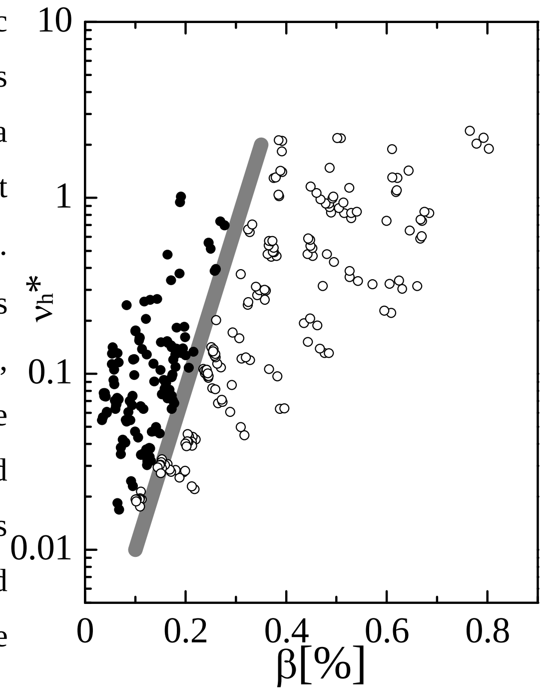

Fig.1 Island growing (closed) and healing (open) region in β - ν space. Grey solid line indicates boundary obtained experimentally.

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 [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 $\Delta\theta_{m=1} = 0$ (π 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 (9.0krad/s) is larger than that for island growth (6.6krad/s) as shown in figure 2. Furthermore, the experimental observation showing the hysteresis with respect to β 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 β increases, the $\Delta\theta_{m=1}$ maintains ~0 until β = 0.25%. After that, $\Delta\theta_{m=1}$ goes to $\Delta\theta_{m=1} = -\pi$(rad) while the β increases. Finally island is healed ($\Delta\theta_{m=1} = -\pi$rad) at β = 0.3%. On the other hand, $\Delta\theta_{m=1}$ goes back to $\Delta\theta_{m=1} = 0$ at β = 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, β for island suppression is larger than that for island growth.

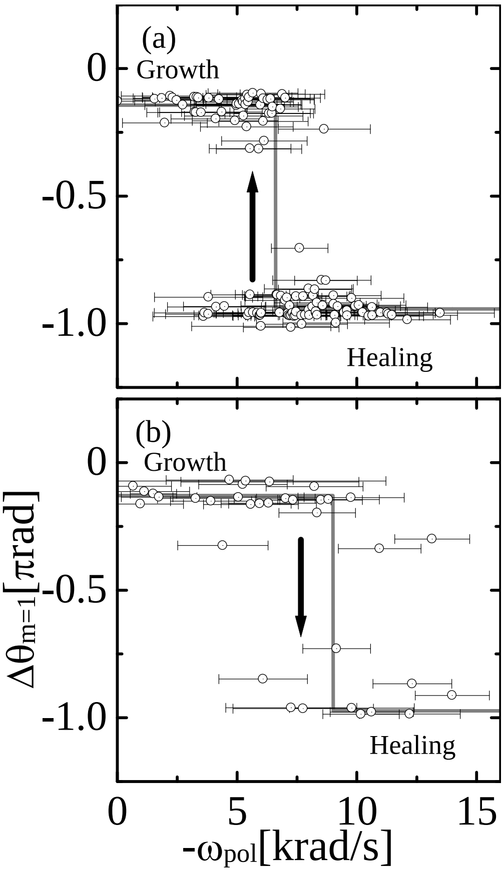

Fig.2 Phase shift $\Delta\theta_{m=1}$ and poloidal rotation ω_{pol} in transition of (a) suppression to growth and (b) growth to suppression. Grey solid line is fitting of Heaviside function. Negative sign of ω_{pol} means electron diamagnetic direction

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.

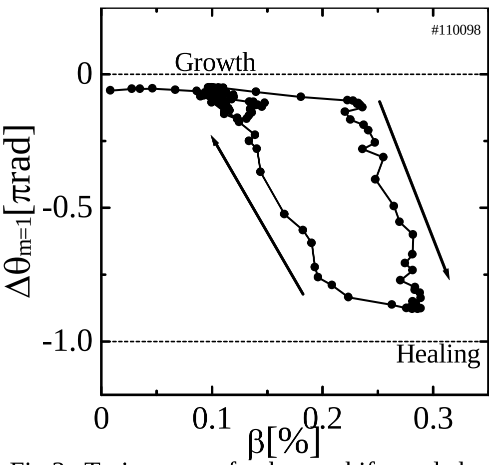

Fig.3 Trajectory of phase shift and beta obtained from single discharge. Time evolution is indicated by arrows.

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 β and ν are almost constant in both cases. The

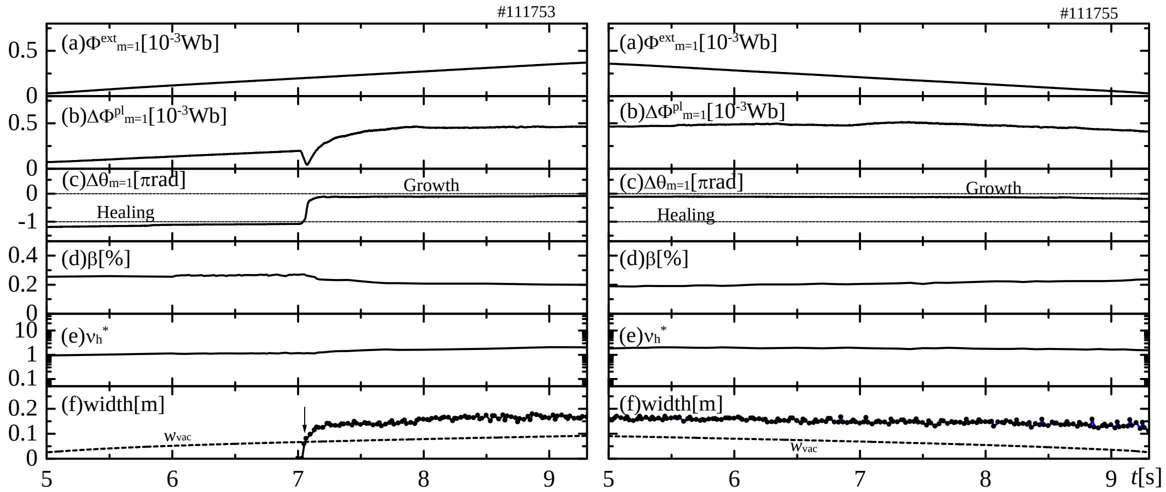

Fig.4 Time evolution of (a) RMP, (b) plasma response field, (c) phase shift, (d) beta at ι/2π=1, (e) collisionality at ι/2π=1and (f) island width estimated from local flattening of T_e profile.

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 = 7s. 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 $\Delta\Phi^{pl}_{m=1}$ (unit of [Wb] detected by non-planar flux loops) indicates the same value of that of external field (RMP) $\Delta\Phi^{ext}_{m=1}$ (converted to an equivalent value at the flux loops). When the RMP exceeds a critical value, the island suddenly appears at t = 7s. 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 $\Delta\theta_{m=1}$ = -πrad 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 $\Delta\Phi^{pl}_{m=1}$ is almost constant whereas the $\Delta\Phi^{ext}_{m=1}$ 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 (β_{crit}^{growth} for growth and β_{crit}^{heal} for healing) is described in detail in Ref.[4] as follows

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

under the condition of $\omega_0'\tau_L >> 1$, where ω_0' denotes the difference between natural frequency (determined by neoclassical transport and external sources) and electron diamagnetic frequency and τ_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 ($\beta_{crit}^{growth} < \beta_{crit}^{heal}$). 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_{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.

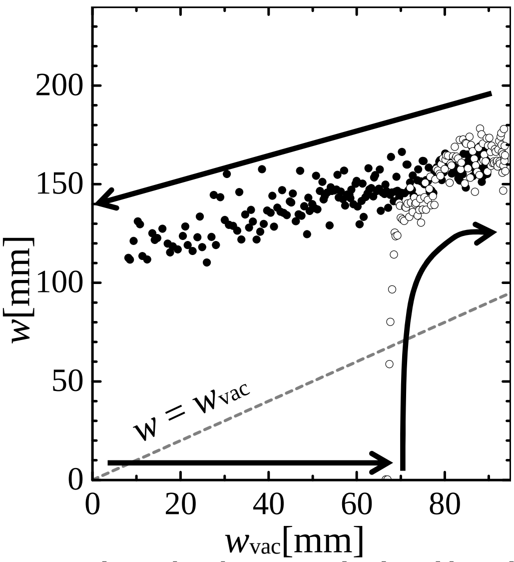

Fig.5 Relationship between island width and vacuum island width in *time-varying* RMP. Open and closed circles indicate increasing and decreasing RMP cases respectively. Arrows mean time evolution.

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