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Abstract. New observations in the Large Helical Device (LHD) show that the magnetic islands externally imposed by m/n = 1/1 resonant magnetic perturbation (RMP) can be maintained in an intermediate state with a finite phase shift away from the value present in vacuum. Given the previous experimental observation that the saturated magnetic islands show either growth or healing, the intermediate states are realized in the "healing region" in the beta and collisionality space, which implies that a parameter other than beta and collisionality should exist in order to determine the island state. Theories based on the competition between electromagnetic torques and poloidal flow-induced viscous torques provide a prediction for the intermediate state. These two types of torques might be balanced to realize the steadily maintained intermediate state whereas the islands are placed in the growth state or healing state in the case in which the balance is broken. The experimental observation shows that there is a possibility for the magnetic island phase to deviate from its designed position. If the parameters are controlled properly, it is possible to control the phase of the magnetic island, which may permit continued utilization of the island divertor concept.

1. Introduction

Magnetic islands have the potential to improve plasma capability if their adverse effects are suppressed. Magnetic islands can produce the transport barrier [1] and establish their own good confinement [2]. In RFP plasmas, increase in electron temperature has been observed in the quasi-single-helicity state which can be considered as an island structure rather than as the multi-helicity state [3, 4]. The island divertor concept in W7-X [5] is an example of utilizing magnetic islands, in which the magnetic islands produced by the external coils are required to keep their structure constant. The magnetic island is also applied to establish the detached state in the Large Helical Device (LHD), and its correlation between the detached plasma and the magnetic island is intensively studied [6 - 8]. In our previous study of the dynamics of the magnetic islands in LHD, it was observed that the magnetic island produced by the *resonant magnetic perturbation* (RMP) shows the clear bifurcation of growth (enlarged) or healing (disappearance) in a saturated states [9]. The intermediate state has been thought to be transient and not to be steadily maintained. However, a steady intermediate state lasting about 2 s is found under the condition of imposing static RMP, which causes us to change our understanding of the magnetic island dynamics. In the following section, the experimental setup is introduced. The experimental observations are shown in section 3. Section 4 provides the discussion. Finally, a summary is given in section 5.

2. Experimental setup and equilibrium of LHD plasma

The LHD is the largest heliotron-type plasma confinement device with poloidal/toroidal period numbers of 2/10, and is equipped with superconducting helical and poloidal coils. Typical plasma major and average minor radii are R = 3.6 and a = 0.6 m, respectively. The perturbation coils, which are made of normal conductor, are placed on the top and the bottom of the LHD at intervals of 0.2 π rad in the toroidal circumference as denoted by bold solid lines in Fig.1. The perturbation coils impose the RMP in order to correct the error field and also to produce a vacuum magnetic island. We are interested in the equilibrium with a magnetic island with the m/n = 1/1 mode in the plasma. The magnetic configuration studied here has a monotonically increasing rotational transform with $\iota/2\pi$ = 0.4 at the magnetic axis and $\iota/2\pi$ = 1.6 at the last closed flux surface in the vacuum configuration as shown in Fig. 2 (a). The resonant surface of $\iota/2\pi$ = 1 stays somewhat inside the last closed flux surface, where the magnetic island with m/n = 1/1 is produced. The Poincaré plot with the magnetic island made by the static RMP field is shown in Fig. 2 (b). The white region is the magnetic island in the vacuum magnetic configuration. Hereafter, it is called the "vacuum magnetic island. When the magnetic island varies its structure of the width and phase, the PRF appears, which can be detected by the saddle loop coil array (See Fig.1 in Ref. [10]). Each array contains 12 saddle loops, which can detect the PRF directing to minor-radial component. To detect the magnetic perturbation originating from the island change, the large cross section of the flux loop is required because the characteristic time of the change of the magnetic island is longer than that of the MHD phenomenon. From the poloidal profile of the PRF, the component of the m = 1 (amplitude; $\Delta\Phi_{pl}$ and phase difference between RMP and the PRF; $\Delta\theta_{pl}$.) can be derived. Here, $\Delta\Phi_{pl}$ have the unit of [Wb] because they are detected by non-planar flux loops [10], but the magnetic field having a unit of [T] varies depending upon the arbitrarily defined surface.

3. Experimental result

This section describes the experimental observations of the magnetic island dynamics in LHD. The conventional understanding of the island dynamics in the previous study is introduced, and is followed by discussion of the newly found phenomena.

3.1 Island behavior in the transition between growth and healing in the previous study

In our previous study of the dynamics of the magnetic island, we suggested that the magnetic islands produced by the RMP are steadily in the state of growth or healing. The typical waveforms of the discharge in which the magnetic island shows the transitions from healing to growth are shown in Fig. 3. Here, the intermittently injected perpendicular NBI (dashed line in Fig.3 (a)) is also utilized to measure the poloidal flow using the charge exchange spectroscopy (CXS). Therefore, a small oscillation is reflected by the waveform of the beta (Fig. 3 (b)). In the beginning of the discharge at t < 6.5 s, the width of the magnetic island w is zero showing the healing (Fig. 3 (f)), in which the w and w_{vac} are evaluated as the width of local flattening of T_e profile due to island at the inboard side (at R~3[m]) and as the structure of the vacuum configuration (Fig.2 (b)), respectively. The phase difference of PRF $\Delta\theta_{pl}$ indicates anti-phase of $\Delta\theta_{pl}$ = $-\pi$ rad and the amplitude of $\Delta\Phi_{pl}$ has the finite value, which means the RMP is compensated by the PRF to make the magnetic island suppressed. When the β decreases at t = 6.5 s, the magnetic island shows growth ($w > w_{vac}$) (Fig. 3 (f)). Here, w_{vac} means the width of the vacuum island. At the same time, $\Delta\theta_{pl}$ moves from $-\pi$ rad to $\Delta\theta_{pl} = 0$. It has been thought that the intermediate state ($\Delta\theta_{pl}$ being between 0 and π) can be realized only transient. During the transition, the absolute value of the poloidal flow decreases as shown in Fig. 3 (e). The relationship between the poloidal flow and the behavior of the magnetic island has been studied [10]. As shown in Fig. 4, when the absolute value of the poloidal flow is small, $\Delta\theta_{pl} \sim 0$ whereas $\Delta\theta_{pl} \sim -\pi$ rad for island healing. The time evolutions are indicated by solid arrows for both transitions. For both transitions, the values of ω_{pol} are overlapped due to the hysteresis character, which region is hatched by gray at $\omega_{pol} = -5 \sim -10$ krad/s. The hysteresis character is originated from the interaction between the magnetic island and the poloidal flow. The experimental and theoretical studies have been reported [11 - 13], in which the thresholds of poloidal flow for each transition (healing to growth, or growth to healing) are different. These experimental observations had meant that the magnetic island shows two-valued-like behavior ($\Delta\theta_{pl} = 0$ or π) in the steady state. Namely, to maintain in an intermediate state with a finite phase shift away from the RMP has been thought to be transient. Such conventional understanding of the island dynamics, however, will be reconsidered because we have discovered new observations.

3.2 Sustained intermediate state of the magnetic island

We have found a steady intermediate state lasting about 2 s before the transition to growth of the island under the condition of imposing static RMP as shown in Fig. 5. From $t \sim 4.5$ s to 6.4 s, the $\Delta\theta_{pl}$ is maintained at $\Delta\theta_{pl} \sim -0.5\ \pi$ rad (Fig. 5 (d)). This behavior of steady intermediate state has never been noticed experimentally. During this intermediate state, the averaged diamagnetic beta $<\beta_{dia}>$, the electron density, and the amplitude of PRF are $<\beta_{dia}> \sim 1$ %, $n_e \sim 5 \times 10^{19}$ m^{-3}, and $\Delta\Phi_{pl} \sim 1.8 \times 10^{-4}$ Wb, respectively. The island width w gradually increases from $w = 12$ cm to 15 cm which is larger than the width of the vacuum island w_{vac} (Fig. 5 (g)). After the transition (indicated by gray hatched region), the averaged diamagnetic beta decreases and the phase difference indicates $\Delta\theta_{pl} \sim 0$ at $t = 7\sim 8$ s (Fig. 5 (d)). Even though the $\Delta\theta_{pl} \sim -\pi$ rad in the beginning of the discharge at $t \sim 3.8$ s, the amplitude $\Delta\Phi_{pl}$ is too small ($\Delta\Phi_{pl} \sim 1 \times 10^{-4}$ Wb) to suppress the RMP field ($\Delta\Phi_{RMP} \sim 1.7 \times 10^{-4}$ Wb). The magnetic island imposed by the RMP has not been suppressed by the PRF, thus this discharge has not experienced the healing of the magnetic island.
It should be noted that the PRF does not indicate the exact island structure because the magnetic island is produced by the perturbation field superimposed by the RMP ($\Delta\Phi_{RMP}$) and the PRF. To determine the exact island structure, the *effective perturbed field* (EPF), obtained by superposing those fields, should be adopted. We estimated the amplitude ($\Delta\Phi_{eff}$) and the phase ($\Delta\theta_{eff}$) of the EPF using the simple cosine law as follows.

$$\Delta\Phi_{eff} = \sqrt{\Delta\Phi_{RMP}^2 + \Delta\Phi_{pl}^2 + 2\Delta\Phi_{RMP}\Delta\Phi_{pl}\cos\Delta\theta_{pl}} \qquad (1)$$

$$\Delta\theta_{eff} = \cos^{-1}\left(\frac{\Delta\Phi_{eff}^2 + \Delta\Phi_{RMP}^2 - \Delta\Phi_{pl}^2}{2\Delta\Phi_{RMP}\Delta\Phi_{eff}}\right) \qquad (2)$$

The $\Delta\theta_{eff}$ means the phase difference between the EPF and RMP. All these values in Eqs. (1) and (2) are the component of the Fourier mode of $m/n = 1/1$. As shown in Fig. 5 (f), the phase of EPF $\Delta\theta_{eff}$ is around $-0.3\ \pi$ rad with the finite amplitude $\Delta\Phi_{eff}$ (Fig. 5 (e)), which means that the phase of the magnetic island is maintained with the deviation of 0.3 π rad from RMP. Island width is larger than the vacuum width indicated by dashed line in Fig. 5

(g). These experimental facts show that the magnetic island made by the static RMP can maintain its deviated shift from its original position of the vacuum island.

3.3 Structure of the magnetic island in the intermediate state

When the magnetic island moves (shifts, grows, and disappears), the electron temperature profile measured at a fixed position shows a different profile (Euler's perspective). The local flattening of the electron temperature profile corresponding to the magnetic island appears. The electron temperature profiles and the Poincaré plots are shown in Fig. 6. In the Poincaré plots, the regions of the magnetic islands are drawn by black. The electron temperature profile is measured at the equatorial line at the toroidal angle named “4-O” (Fig. 1). In the intermediate state at t = 5.0 s, the local flattening region appears at one side of $R \sim 4.2$ m (arrow in Fig. 6 (a)). At this time, the phase of EPF $\Delta\theta_{eff}$ is approximately -0.3 π rad and its shift can be realized by a comparison with the Poincaré plot of the vacuum island shown in Fig. 2 (b). At t = 7.5 s, the flattening region can be seen at both sides of $R \sim 3.0$ m and 4.2 m in the growth state (arrows in Fig. 6 (b)). At this time, the phase of EPF $\Delta\theta_{eff}$ is around 0 and the width of the magnetic island is larger than that of the vacuum island (see Fig. 2 (b)), which means that only the width of the island grows maintaining its phase (position of the X (O) - point).

3.4 Behavior of island in the intermediate state

To understand the physical position of the intermediate state of the magnetic island, we compare the plasma parameters of beta β and collisionality ν to the previously obtained data of the static island (gray symbols and solid line in Fig. 7). The gray closed and open circles indicate the plasma with $\Delta\theta_{pl}$ = 0 (growth) and $\Delta\theta_{pl} = \pi$ (healing), respectively. As mentioned above, the conventional understanding about the island dynamics in LHD was that the islands show the alternating behavior. The parameters of the discharge of Fig. 5 are plotted by the black circles in Fig. 7. The black closed (opened) circles indicate the growth (intermediate) island states. The growth islands are in the “growth region” in Fig. 7 whereas the intermediate states (black open circles) are realized in the “healing region,” which implies that the parameters except for β and ν should exist in order to determine the island state. It has recently been reported that the poloidal flow has an important role in explaining the island dynamics in the LHD [11] in which the relationship between the poloidal flow ω_{pol} and the phase difference of PRF $\Delta\theta_{pl}$ has been shown. The relationship between the ω_{pol} and $\Delta\theta_{pl}$ in the intermediate state is shown in Fig. 8 as the black symbols. The $\Delta\theta_{pl}$ is in the area at $\Delta\theta_{pl} \sim 0.5\ \pi$ rad whereas the previously obtained data (gray squares) are plotted at the $\Delta\theta_{pl} \sim 0$ and $\sim \pi$. The points of the poloidal flow in the intermediate state are distributed at $-\omega_{pol} = 8 \sim 11$ krad/s.

4. Discussion

In previous studies of the magnetic island dynamics the behaviors of the magnetic islands have been explained by two subjects. The first subject is the behavior in the β and ν space, in which the magnetic island grows (disappears) in the lower (higher) β and higher (lower) ν region. The second subject is based on the model of the competition between electromagnetic torques and poloidal flow-induced viscous torques [12, 13]. From the viewpoint of the former idea, the intermediate state lies at near the boundary drawn by the solid line as shown in Fig. 7 before the transition to the growth state. It should be noted that the previously obtained data colored gray has been obtained under the condition of the steady state. The discharge studied here shows gradual change of its state from intermediate to

growth. Once the magnetic island enters into the "growth region," the island clearly shows growth as indicated by closed black circles in Fig. 7. The discharge shown in Fig. 5 enters the intermediate state from the beginning of the discharge. That is, it does not experience the healing. The intermediate state can be realized near the "steady state" boundary in the β and ν space. The plasma beta and collisionality themselves do not necessarily affect the magnetic island dynamics directly. The latter idea may explain the condition of the intermediate state. The data of $\Delta\theta_{pl}$ and ω_{pol} in the intermediate state are superimposed on Fig. 5 to see the position of the intermediate state as shown in Fig. 8. The phase shift of PRF plotted by black squares is maintained at $\Delta\theta_{pl} \sim -0.5\ \pi$ rad. The range of the poloidal flow ω_{pol} is in the "overlapped region" hatched gray. The $\Delta\theta_{pl}$ and ω_{pol} are in between the growth and healing regions. Figure 8 implies that if the poloidal flow is set to a certain value, the phase shift of PRF is maintained at $\Delta\theta_{pl} \sim 0.5\ \pi$ rad, which leads to the intermediate state.
Considering the second idea, theories based on the competition between electromagnetic torques and poloidal flow-induced viscous torques [12, 13] provide a prediction for the intermediate state. The electromagnetic torque and viscous torque play the role of a resisting force (for island locking) and a driving force (for island rotation), respectively. If the electromagnetic torque is larger than the viscous torque, the magnetic island is locked (in growth) to the position belonging to the RMP structure and the phase difference is zero ($\Delta\theta_{pl} = 0$), whereas the magnetic island starts to deviate from the original position to rotate and be healed if the viscous torque overcomes the electromagnetic torque. These two types of torques might be balanced to realize the steadily maintained intermediate state. The island divertor concept adopts the magnetic island placed at the peripheral region whereas the position of the island studied here is inside the plasma. A similar phenomenon should occur for the magnetic island remaining in the peripheral region, and is indeed observed in LHD. Figure 9 shows an example of the discharge in which the intermediate state lasts ~1 s before the transition to the detached state [6 - 8]. The plasma transits from an attached state to a detached state at t = 2.7s. The intermediate state ($\Delta\theta_{eff} \sim -0.5\ \pi$ rad) is realized in the attached phase (t < 2.7s), in which the phase of the magnetic island is shifted from the position in the detached state. The Poincaré plots at t = 2 s (attached phase) and 3 s (detached phase) are shown in Fig.10. The position of the X- (O-) point of the magnetic island in the detached phase is the same as the vacuum island ($\Delta\theta_{eff} = 0$) whereas those positions are deviated by -0.5 π rad in the attached phase (t = 2.0 s). It should be noted that the position of the X- (O-) point in the laboratory frame is different by π rad from the Poincaré plot shown in Fig. 2(b) because the direction of the toroidal magnetic field is opposite in the laboratory frame. The magnetic island at the peripheral region can be deviated from the RMP position. Thus there is a possibility to make the magnetic island phase deviate from the vacuum island in the magnetic configuration similar to the island divertor configuration. If the poloidal flow can be externally varied, the phase of the magnetic island can be also arbitrarily controlled, which may permit continued utilization of the island divertor concept. One possibility for controlling the poloidal flow is imposing the radial electric field E_r, which has been attempted in LHD [14], where the electrode is inserted inside the last closed flux surface. The new finding of the intermediate state brings a distinct paradigm shift in which the magnetic island can be moved and maintained in a partial position of the phase.

5. Summary

The sustained phase shifted magnetic islands from externally imposed m/n = 1/1 RMP are observed in LHD. The experimental observation implies that the plasma response can provide plasma currents that produce deviations away from the designed position of the RMP coils and can be maintained in the unfavorable phase. Given the previous experimental observation that the saturated magnetic islands show either growth or healing, the intermediate states are realized in the “healing region” in the beta and the collisionality space, which implies that the parameter except for beta and collisionality should exist in order to determine the island state. The intermediate state can be predicted by theories based on the competition between electromagnetic torques and poloidal flow-induced viscous torques, in which these two types of torques might be balanced to realize the steadily maintained intermediate state. The magnetic island remaining in the peripheral region also shows the intermediate state in LHD. If the poloidal flow can be externally varied by imposing the radial electric filed sufficiently, the phase of the magnetic island can be also arbitrarily controlled, which may permit continued utilization of the island divertor concept. The experimental observation shows that there is a possibility for the magnetic island phase to deviate from its designed position. If the parameters are controlled properly, it is possible to control the phase of the magnetic island. The new finding of the intermediate state brings a distinct paradigm shift in which the magnetic island can be moved and maintained in a partial position of the phase.

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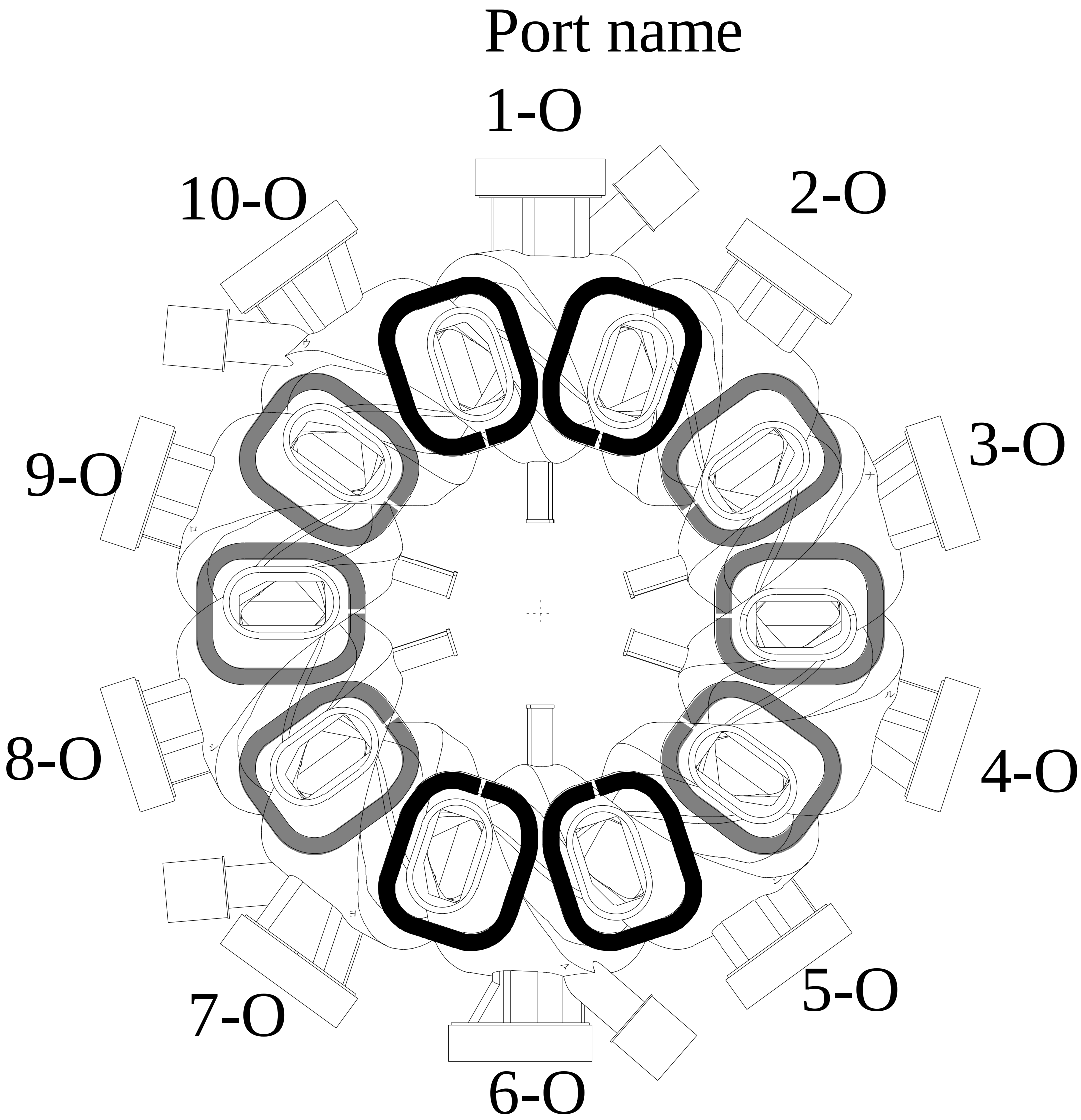

Fig.1 Top view of vacuum vessel and resonant magnetic perturbation coil system of the LHD. Coils for m/n = 1/1 are colored black. Coils for m/n = 2/1 are colored gray. Labels of "1-O" to "10-O" are names of each ports.

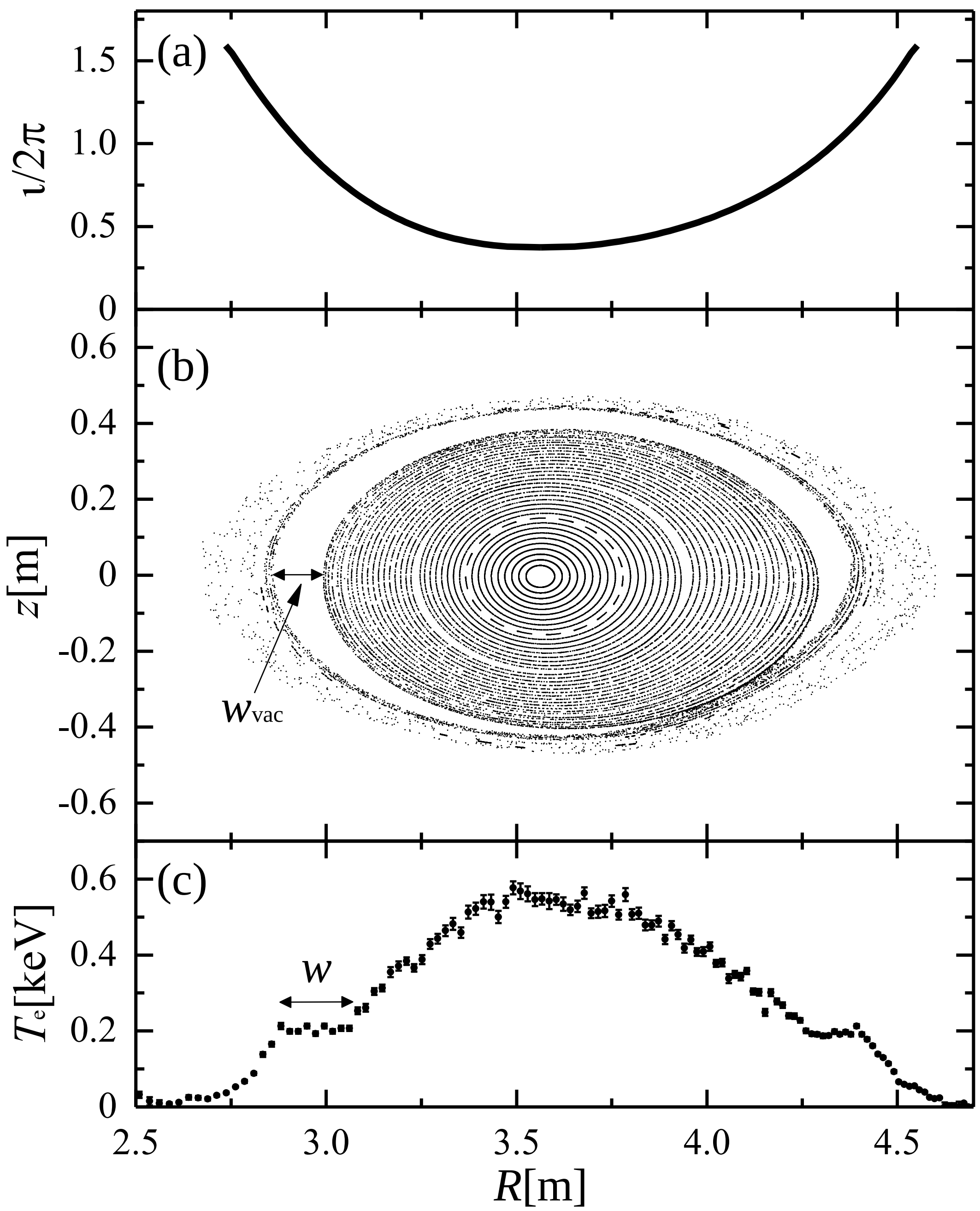

Fig.2 (a) Profile of rotational transform in real coordinate. (b) Poincaré plot of poloidal cross-section of the magnetic configuration with magnetic island of m/n = 1/1 mode. Poloidal angle corresponds to port named "4-O". Vacuum island width w_{vac} is determined at inboard side of equatorial plane (c) Magnetic island width w is determined by width of local flattening of electron temperature profile.

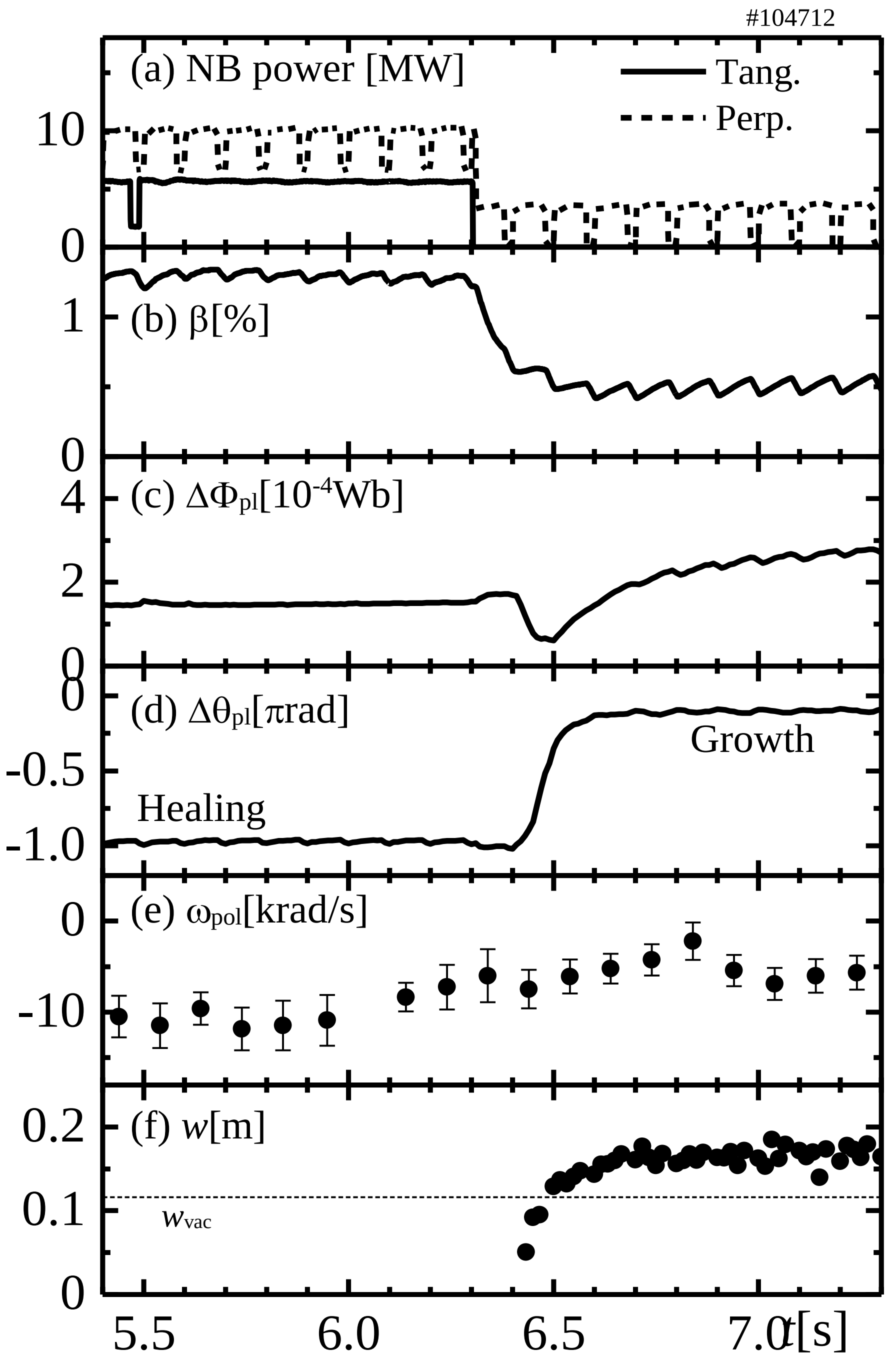

Fig.3 Waveforms of discharge with island transition from healing to growth. (a) Port through power of NBI. (b) Beta value at $\iota/2\pi = 1$. (c) Amplitude of plasma response field (PRF) of m = 1 mode. (d) Phase difference of PRF of m = 1 mode. (e) Poloidal flow at outside $\iota/2\pi = 1$ measured by CXRS. (f) Width of magnetic island. Phase difference $\Delta\theta_{pl}$ shows transient behavior which does not stay at $\Delta\theta_{pl} \sim -0.5\pi$rad.

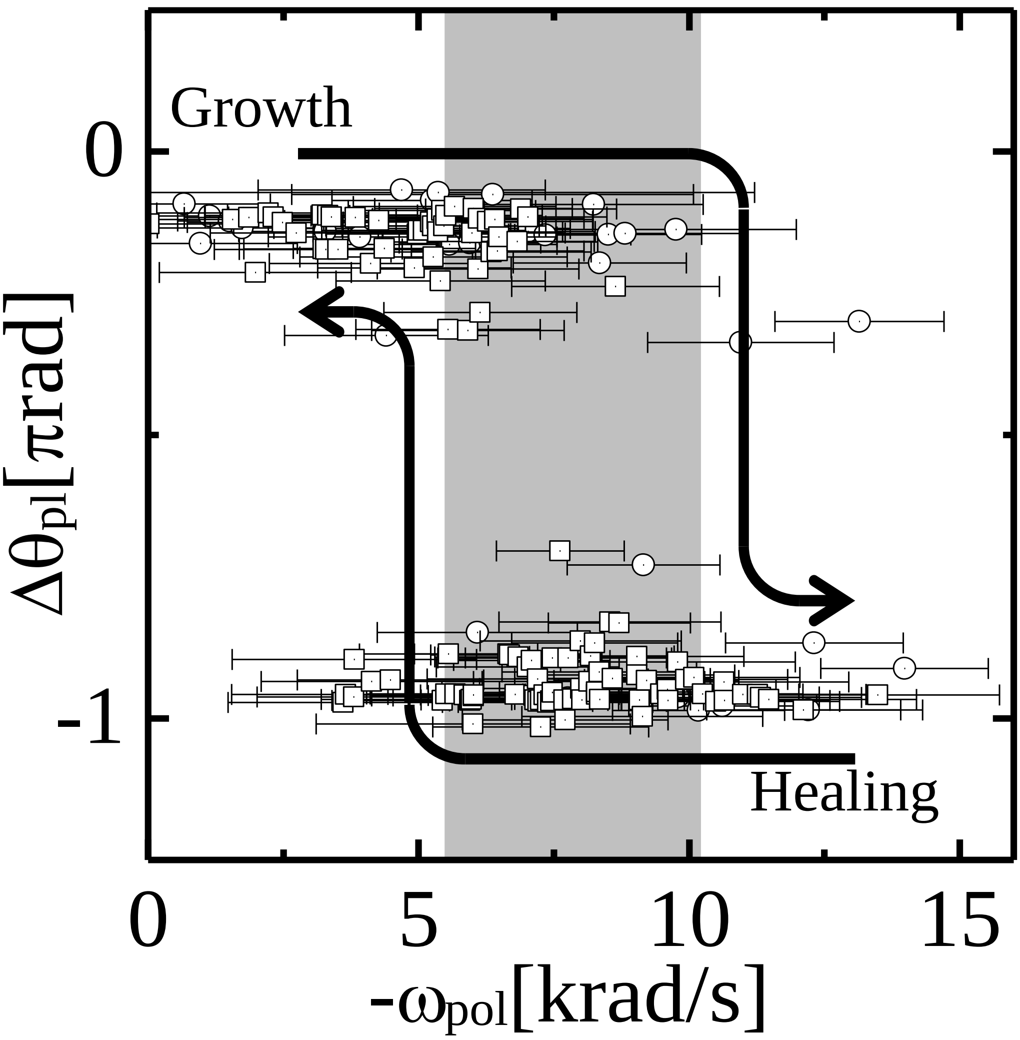

Fig.4 Relationship between poloidal flow ω_{pol} and $\Delta\theta_{pl}$. Arrows indicate time evolution of each transition.

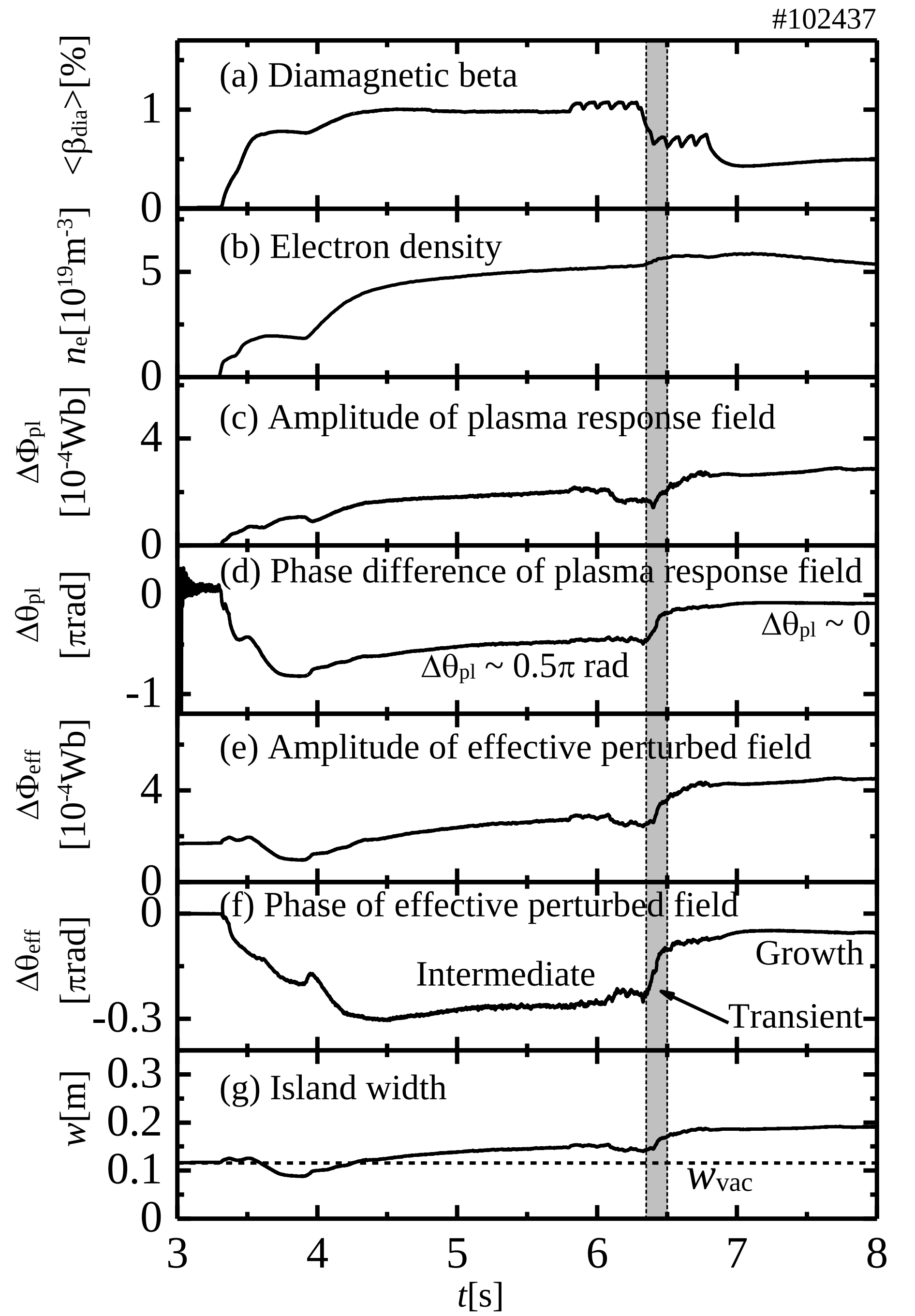

Fig.5 Waveform of (a) averaged diamagnetic beta, (b) electron density, (c) amplitude of PRF, (d) phase of PRF, (e) amplitude of effective perturbed field (EPF), (f) phase of EPF, and (g) island width estimated from EPF. Intermediate state ($\Delta\theta_{pl}$ ~ -0.5 and $\Delta\theta_{eff}$ ~ -0.3 π rad) is maintained from t ~ 4.5 s to 6.35 s. After transition (t = 6.35 s - 6.5 s shadowed by gray), growth state ($\Delta\theta_{pl}$ ~ $\Delta\theta_{eff}$ ~ 0) follows.

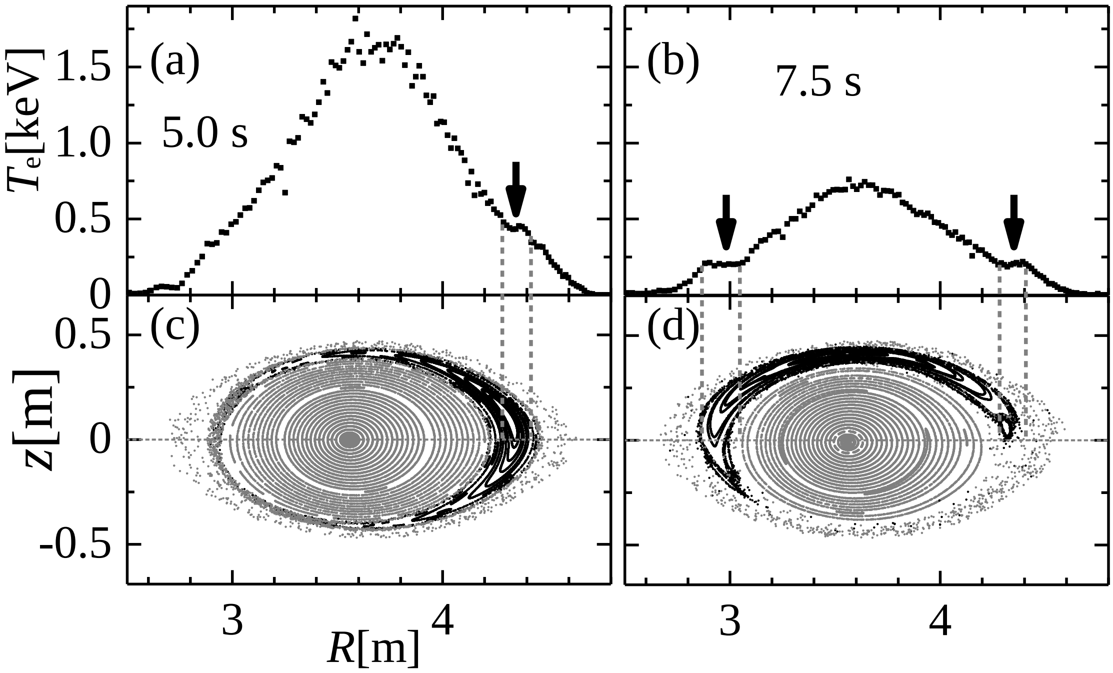

Fig.6 *Electron temperature measured by Thomson scattering. (a) In intermediate state (t = 5.0 s), local flattening region appears at R ~ 4.2 m. (b) In growth state (t = 7.5 s), local flattening regions appear at both sides (R ~ 3.0 m and 4.2 m). These positions of flattening region correspond to island structure in Poincaré plots (c) and (d) calculated with EPF.*

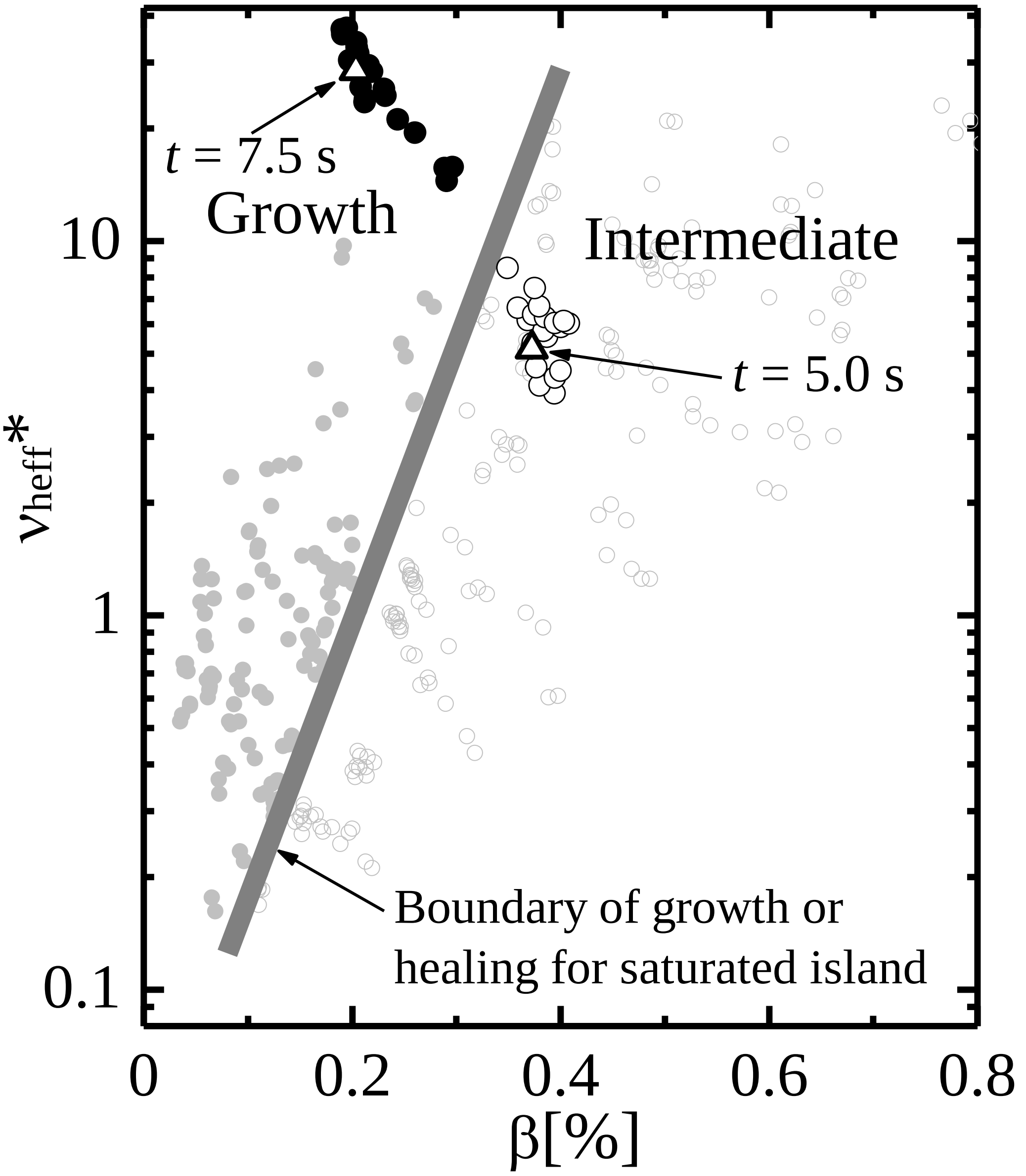

Fig.7 Plasma parameters of discharge in the beta - collisionality space. Gray closed circles were acquired under condition of saturated growth state and gray open circles were acquired under condition of saturated healing state after transition from growth. Magnetic islands in intermediate states indicated by black open circles remain at "marginal region" whereas growth states indicated by black closed circles are further from boundary. Triangles indicate plasma at t = 5.0 s and 7.5 s, as shown in Fig. 6.

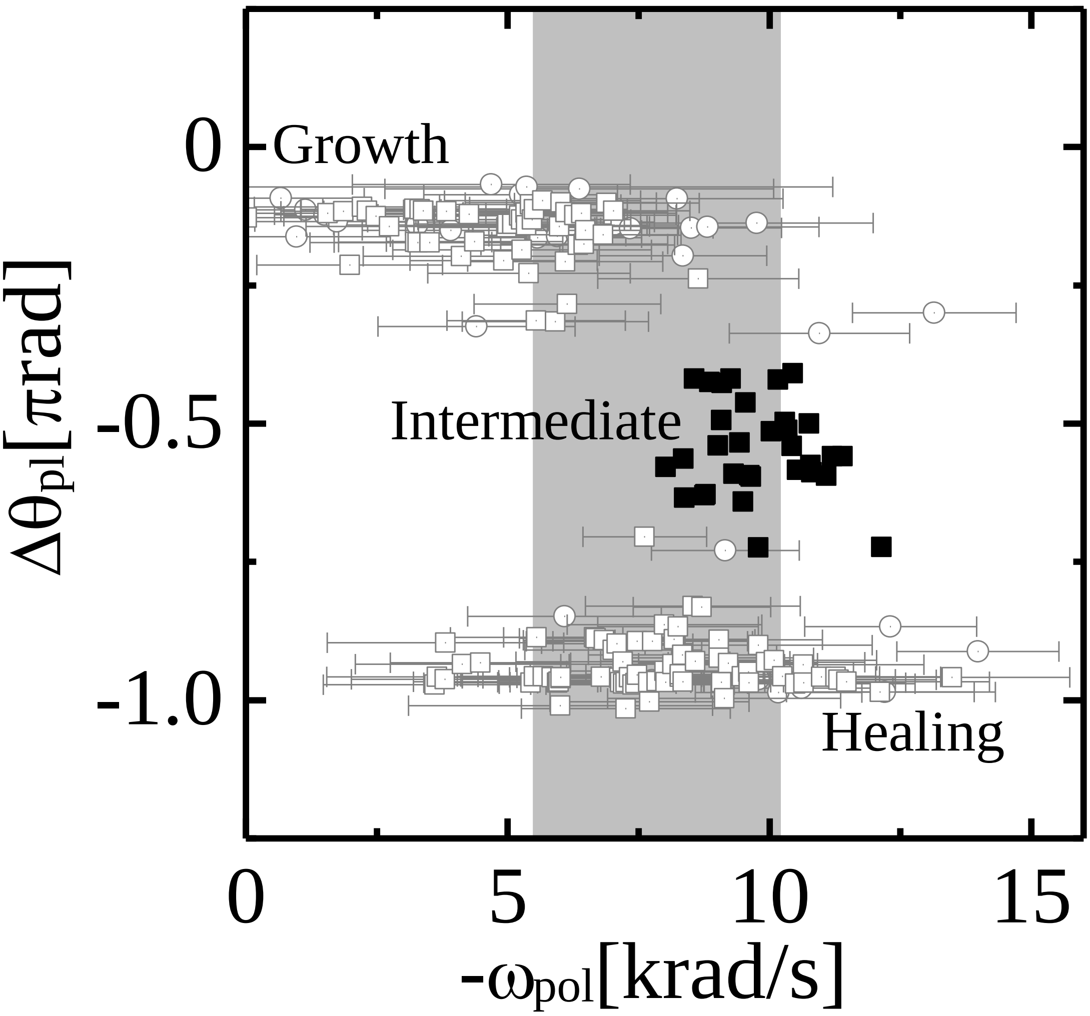

Fig.8 Relationship between poloidal flow and phase difference of plasma response field. Black squares are in intermediate state.

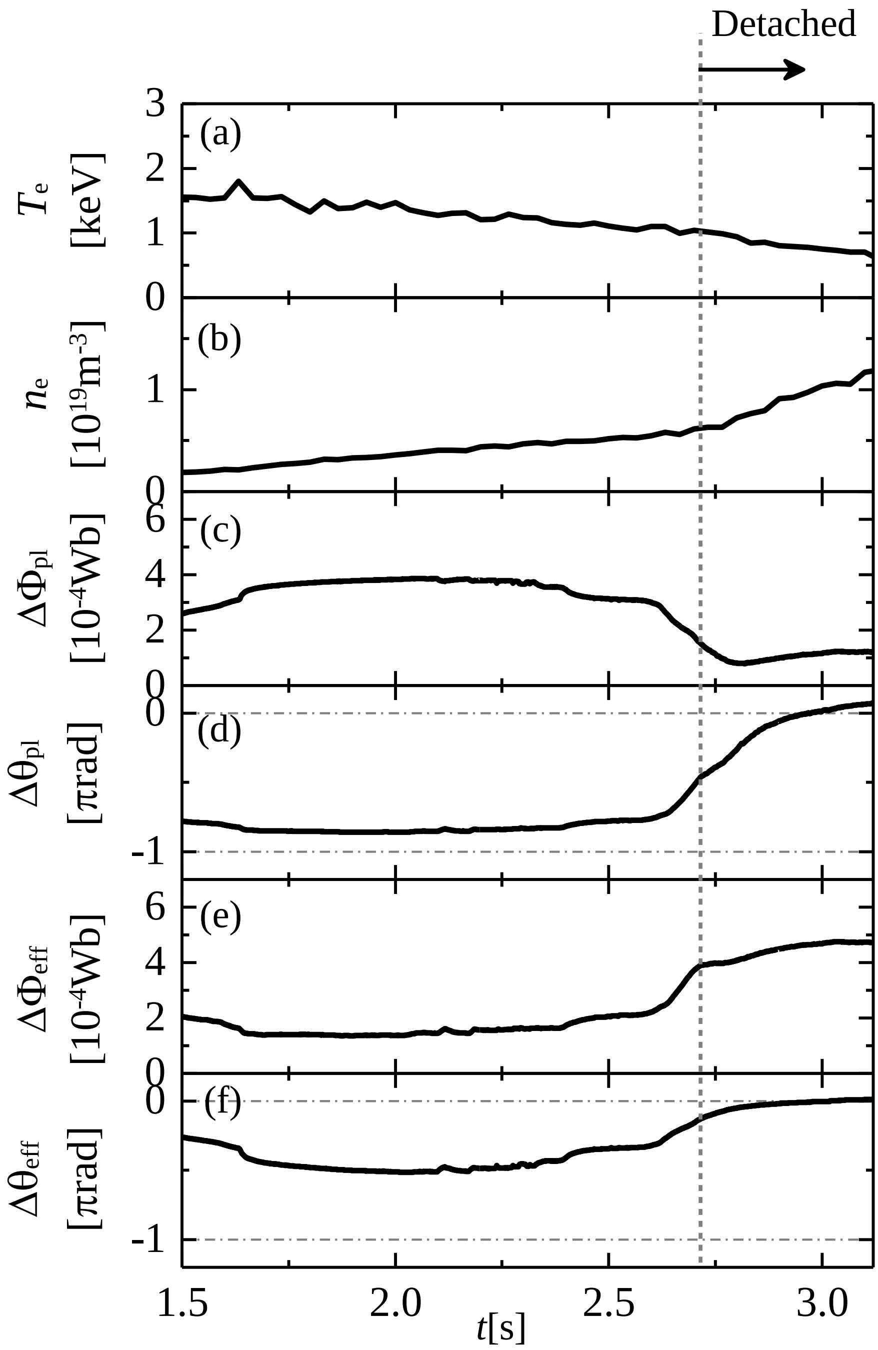

Fig.9 Waveform of (a) electron temperature, (b) electron density, (c) amplitude of PRF, (d) phase of PRF, (e) amplitude of effective perturbed field (EPF), and (f) phase of EPF. Detached state is realized at t = 2.7 s. Intermediate state ($\Delta\theta_{eff}$ ~ -0.5 π rad) is maintained from t ~ 1.6 s to 2.6 s.

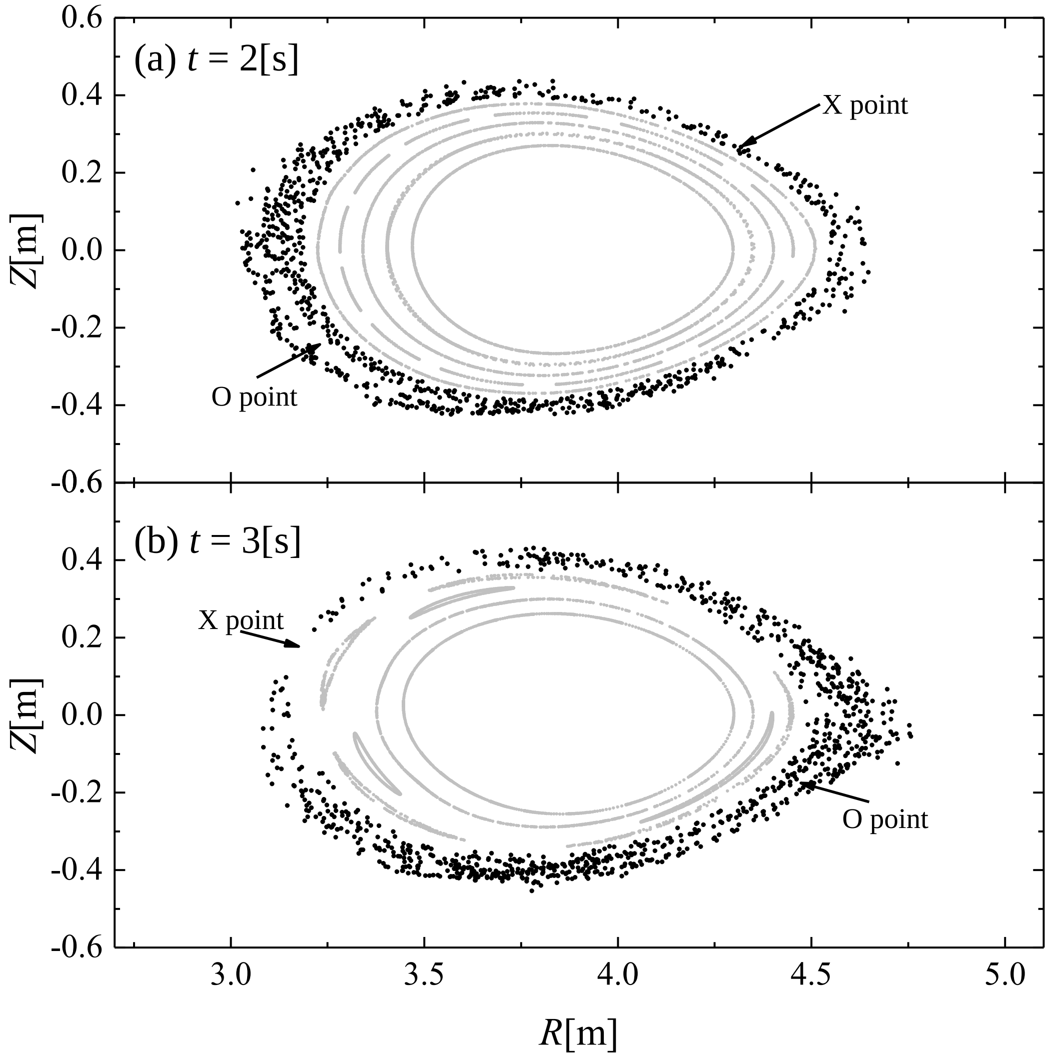

Fig.10 Poincaré plots in (a) attached phase with $\Delta\theta_{eff}$ = -0.5 π rad and (b) detached phase with $\Delta\theta_{eff}$ = 0. The magnetic island lies at the peripheral region.