Experiment of Magnetic Island Formation in LHD

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Abstract. Magnetic island formation is experimentally investigated in the Large Helical Device (LHD). The (m, n)=(1, 1) vacuum magnetic island is generated by using the local island diverter (LID) field, where m and n are the poloidal and toroidal mode numbers, respectively. The island width depends on plasma parameters (the electron temperature and the beta) and the magnetic axis position. In the case of R_{ax}=3.53 m, the magnetic island in the plasma is larger than that in the vacuum field. Here, R_{ax} is the major radius of the magnetic axis. In the case of R_{ax}=3.6 m, the magnetic island is not generated when the error field is less than the threshold, which is increased as the beta is increased. Evidence of island current is obtained when the magnetic island is formed due to a small error field. However, the mechanism that generates the island is not known yet.

1. Introduction

Magnetic islands play important roles in fusion and space plasmas. MHD instabilities create magnetic islands by magnetic reconnection, and cause sawtooth oscillations in tokamaks [1] and in helical systems [2]. In tokamaks, a seed island is enlarged due to the neoclassical effect, and it degrades the plasma performance [3]. In helical systems, it has been considered that the magnetic island structure, which is formed by an error field, could grow and degrade the plasma confinement seriously. So, magnetic islands are very important in helical plasmas.

The (m, n)=(1, 1) error field can be controlled using the external field in the Large Helical Device (LHD), which is the largest superconducting heliotron-type fusion device with an averaged minor radius of a=0.65 m and a major radius of the plasma axis (R_{ax}) of 3.6 m [4]. Here, m and n are the poloidal and toroidal mode numbers, respectively. In LHD, it has been observed that the heat conduction in the magnetic island is extremely smaller than that in the main plasma [5]. This indicates that the island structure is isolated from the main plasma. Also, in LHD, it has been observed that the island size is sometimes significantly reduced in the plasma [6,7]. This is called 'healing' of the island. To control the island width is a key issue in the development of a helical fusion reactor.

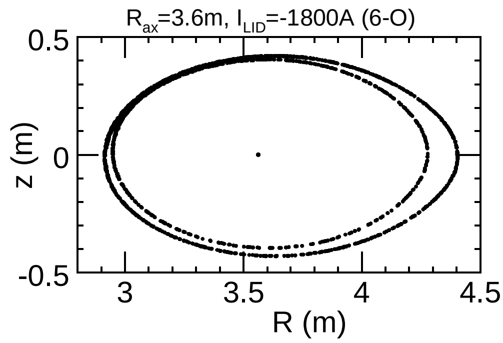

FIG.1. Calculated flux surface of the magnetic island structure.

This paper will present the magnetic island formation in LHD. Confinement of plasma in helical systems is based on the assumption that the flux surface in the plasma can be created by the external field. If so, the magnetic island that is made by an error field should stay in plasma. This paper will show that an island due to the error field sometimes enlarges in the plasma. Under different conditions, however, a large island as wide as 20 % of the minor radius in the vacuum magnetic surface disappears in the plasma due to ‘healing’.

2. Generation of Magnetic Island

2.1. LID Field

In LHD, 10 pairs of modular vertical field coils are installed top and bottom in order to produce a (1, 1) field. By adding the (1, 1) field, a static magnetic island can be formed around the $\iota/2\pi=1$ surface. Since these coils are installed to form an (1, 1) island for the local island diverter (LID) [8], these coils are sometimes called LID coils and the (1, 1) field made by the LID coil current (I_{LID}) is sometimes called the LID field. Figure 1 shows the calculated flux surface in the plasma cross-section at $\phi=136^{o}$ with R_{ax}=3.6 m. Here, the toroidal angle ϕ is defined as the angle from the border between the port sections 3 and 4, and the positive sign is defined as the direction of counter-clockwise in the top view. The flux surface in the vacuum field is measured by a scanning multi-channel detector array that detects an electron beam, which is injected from the electron emission diode. The electron beam is also scanned. The calculated flux surfaces are consistent with those measured in the vacuum field.

2.2 Measurement of Magnetic Island

In this experiment, the width of the magnetic island in the plasma is estimated as a flat region in the electron temperature (T_e) profile. The reason is as follows: the border of the island is a closed flux surface, which is nested by a field line. The electrons run along the field line with very high speed. So, the border of the island is isothermal. If the heat deposition inside the island is very high, the T_e at the O-point of the island can be higher than that on the border. However, since the island width is much narrower than the main plasma, the temperature difference between the O-point and the border is usually not big enough to be recognized. Therefore the T_e profile in the island region looks flat. In LHD, the T_e profile is measured using YAG laser Thomson scattering installed at $\phi=342^{o}$ and the ECE diagnostics at $\phi=136^{o}$. Figure 2(e) shows the T_e profiles with and without the magnetic island. Flat regions around R=2.8 m and R=4.2 m indicate the magnetic island.

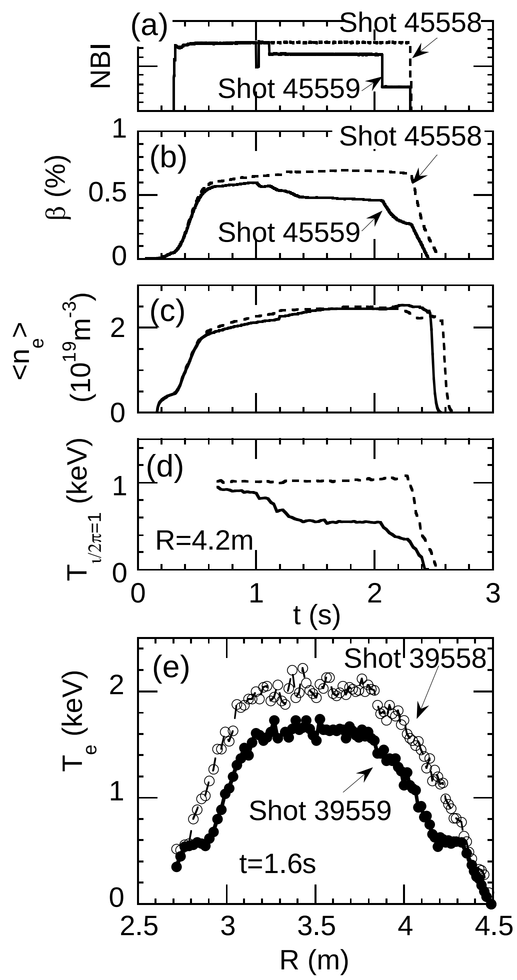

FIG.2. Time evolution of (a) NBI power (arbitrary unit), (b) beta, (c) averaged electron density, (d) temperature at R=4.2 m of plasmas with island (solid line: Shot 39559) and without island (broken line: Shot 39558). (e) T_e profiles with (closed circles) and without (open circles) island.

2.3. Magnetic Island Formation

A typical example of confinement degradation due to magnetic island generation is shown in Fig. 2. Parameters for the plasma configuration are as follows: R_{ax}=3.53 m, B_{ax}=-2.856 T and I_{LID}=400A. For this LID coil current, the residual error field is minimized in LHD, so that the magnetic island should be very small in the vacuum field. Figure 2 (a-d) shows the time evolution of the NBI power, the beta, the averaged electron density and T_e measured by ECE on the $\iota/2\pi$=1 surface, respectively. The broken line indicates the plasma with island (shot 39559) and the solid line indicates the plasma without island (shot 39558). Figure 2(e) shows T_e profiles with and without island. Plasma parameters of both shots are similar before the generation of the island. The magnetic island starts to grow after the NBI power is decreased by 20 %. It takes 0.3 s for the island to be established. This is equivalent to the resistive time scale. Finally, the island width reaches 12 cm. Due to the generation of the island, the T_e profile inside the island drops, and so the beta is decreased significantly. This is a source of confinement degradation in a helical system.

2.4. Healing of Magnetic Island

A typical example of the 'healing' of a magnetic island is shown in Fig. 3. Parameters for the plasma configuration are as follows: R_{ax}=3.6 m, B_{ax}=2.75 T and I_{LID}=-1200 A. Time evolutions of the beta, the averaged electron density and the central T_e are shown in Fig. 3(a), (b), and (c), respectively. The plasma is heated by NBI with power of 9 MW. The hydrogen (H_2) ice pellet is injected at t=1 s. After the ice pellet injection, the electron density and the beta are quickly increased, as shown in Fig. 3(a-b). Figure 3(d) shows the time evolution of the T_e profile after the ice pellet injection. The T_e is measured by the ECE diagnostics at ϕ=136^o. The calculated island width (w) in the vacuum is about 12 cm, but the island is not observed before the pellet injection (t=0.95 s), as shown in Fig. 3(d). This is the 'healing' of the magnetic island.

The electron temperature drops due to the ice pellet injection, and right after the ice pellet injection (t=1.05 s) the temperature profile near the island region is lower than the surrounded region. Soon, the temperature starts to recover, and the wide island appears at t=1.15 s. The width of the island is 12 cm, which is as large as the calculated width of the magnetic island in the vacuum field. As T_e increases, the island width decreases. Finally, the T_e

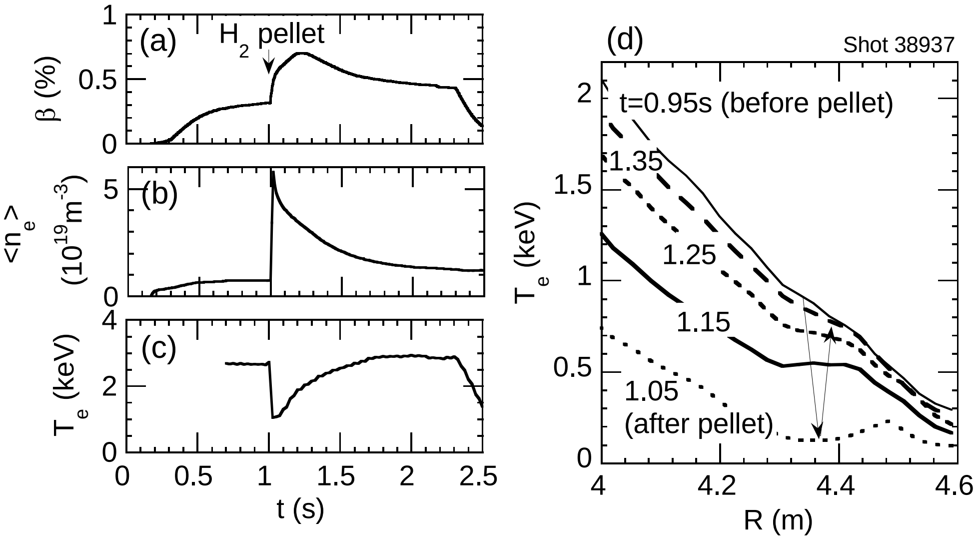

FIG.3. Time evolution of (a) beta, (b) averaged electron density, (c) temperature, (d) T_e profile with the (1, 1) external field (I_{LID}=-1200A).

profile returns to that before the pellet injection, and the island disappears. This experiment clearly shows that the island width in the plasma changes as T_e changes.

3. Island Width

3.1. Parameter Dependence of the Island Width

The island width varies with the plasma parameters (T_e and beta). Figure 4(a) and (b) shows the island width (w) versus T_e and beta in the magnetic island, respectively. The major radius of the magnetic axis is 3.6 m. The experiment is done for various magnetic field, but the normalized LID coil current by B_{ax}, as $I_N=I_{LID}/B_{ax}$, is about 430 A/T. This LID field generates the magnetic island width of 12 cm in the vacuum field. There are two types of tendency indicated by a solid line (type A) and a broken line (type B). In the case of high field (open circles), the island width decreases as T_e increases (type A). In the case of low field (closed circles), the island width decreases as the beta increases (type B).

It looks like the data belonging to type A (solid line) have the opposite tendency to those of type B (broken line). The reason may be as follows: The healing effect by T_e is weaker when T_e is lower than 0.6 keV. Higher beta can be obtained at higher density and at lower field, where T_e is lower and the healing effect by T_e is weak. So, it looks like the data indicated by the closed circles have a tendency opposite to the type A (solid line) in Fig. 4(a). The high T_e plasma is obtained in the low density plasma with the high field, where the beta is lower and the healing effect by the beta is weak. Therefore, it appears that the data indicated by open circles have a tendency opposite to the type B (broken line) in Fig. 4(b).

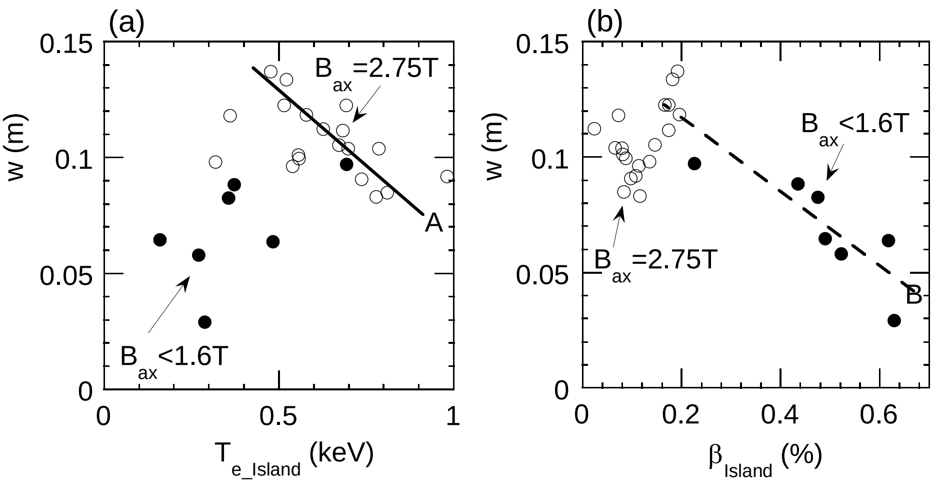

FIG.4. (a) Island width vs. electron temperature in the island. (b) Island width vs. beta in the island. The LID coil current is I_{LID}/B_{ax}=400~460 A/T. Open circles indicate the case of B_{ax}=2.75 T, and closed circles indicate the case of B_{ax}<1.6 T.

3.2. Threshold of Island Formation

As shown in Fig. 4, the island width depends on the beta when the normalized LID current (I_N) by the magnetic field is fixed. Figure 5(a) shows dependence of the island width on the LID coil current (I_N) in the case of R_{ax}=3.6 m and B_{ax}=0.75 T. In order to minimize the effect of T_e, the line averaged electron density ($<n_e>=2x10^{19}$ m^{-3}) is also fixed. As the LID coil current (I_N) is increased, the island width in vacuum is increased. In LHD plasmas, however, the island does not appear when the I_N is less than a threshold value (I_N^*). The island in the plasma suddenly appears when it surpasses the threshold, where the island width in the vacuum is 17 cm. This is about 20 % of the minor radius. This is another example of 'healing' of the island.

Figure 5(b) shows the relationship between the threshold (I_N^*) and the beta at the island. Here, the line averaged electron density ($<n_e>=2x10^{19}$ m^{-3}) is also fixed. The beta is changed by changing the magnetic field and the heating power. As the beta is increased, the threshold (I_N^*) is increased, as shown in Fig. 5(b).

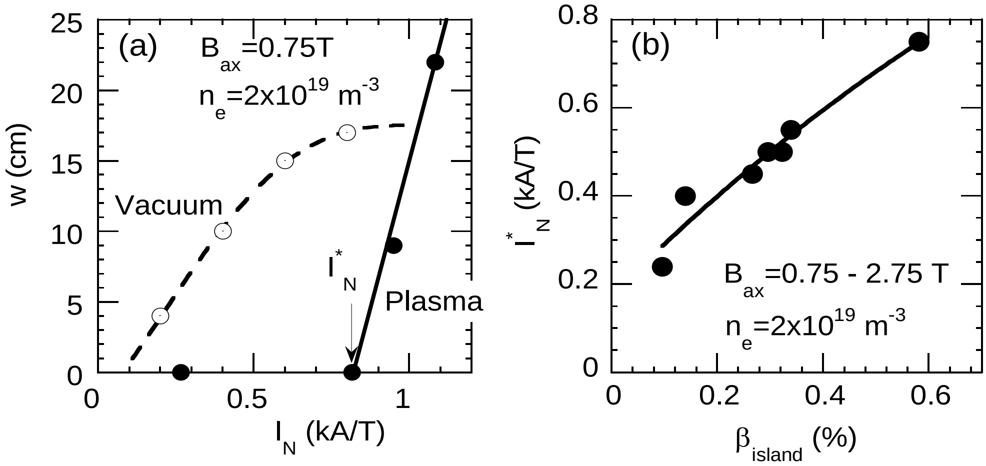

FIG.5. (a) Normalized coil current (I_N) vs. island width (w) in vacuum (open circles) and in plasma (closed circles). (b) beta vs. threshold of the normalize coil current.

4. Island Current

4.1. Evidence of Island Current

In LHD, the radial magnetic field on the mid plane is measured by 10 large coils installed on the outboard side at every port. The toroidal angle of the coils are from $\phi=18^o$ to $\phi=342^o$. Each coil has 10 turns and a cross-section of 1 m^2, so NS=10 m^2. Since the large coils are installed outside the vacuum vessel, the time response is not very good.

In the case of R_{ax}=3.53 m and B_{ax}=2.8 T, time evolutions of beta, averaged electron density and T_e are shown in Fig. 6(a-c). The T_e profile is shown in Fig. 6(d). No LID field is applied. At t=1.4 s, hydrogen ice pellets are sequentially injected into the plasma. The density is increased and the temperature drops due to the pellet injection. The beta is decreased after the pellet injection in this shot. In this shot, the magnetic island is formed after the H_2 ice pellet injection due to the small residual error field, as shown in Fig. 6(d). This is the opposite phenomenon of 'healing'. After the magnetic island is established, T_e drops significantly. This is a case when the magnetic island deteriorates the plasma confinement.

Since the island in the vacuum field is small, the horizontal magnetic field measured on the mid-plane should be generated by the island. Figure 6(e) shows the polar plot of the radial magnetic field (B_r), which is measured by large coils. The open circle and broken line indicate the B_r in the case without island, and the closed square and solid line indicate the B_r in the case with island. These lines are the (1, 1) component, as $B_r^{n=1}=b_r^1\cos(\phi-\phi_0)$, where parameters b_r^1 and ϕ_0 are obtained by the least square fitting to the experimental data that is marked by circles and squares. When the island is not observed (t=1.4 s), the $B_r^{n=1}$ is small, as shown in Fig. 6(e). When the island is observed (t=3.7 s), the $B_r^{n=1}$ is large.

The amplitude of $B_r^{n=1}$ is the highest at $\phi\sim155^o$ and $\phi\sim335^o$ and vanishes at $\phi\sim60^o$ and $\phi\sim240^o$. Figure 7 shows the schematic view of the plasma cross-section, where the m=1 current flows and generates the radial field (B_r). When the B_r is a maximum, the current should be in the top and the bottom. So, at $\phi\sim335^o$ the current that generates the $B_r^{n=1}$ flows in the top and the bottom of the plasma cross section. As shown in Fig. 6(d), the m=1 island appears on both sides of the T_e profile at $\phi=342^o$. So, the X-point and the O-point of the island are located in the top and the bottom in the plasma cross-section at $\phi\sim342^o$. Therefore, the large negative B_r at $\phi=342^o$ is made by the m=1 current flowing at the O-point and/or the X-point of the island. Since the (1, 1) island is formed on the $\iota/2\pi=1$ flux surface, the m=1 current could be called the (1, 1) current. Therefore, the (1, 1) magnetic island is generated by the (1, 1) current on the $\iota/2\pi=1$ flux surface, when the error field is small in a helical system.

Assuming the plasma is cylindrical and the island width is thin, the width of the (1, 1) island can be estimated, as $w^2=2\mu_0 I_s/r_s B_{ax}$, and the magnetic field at the probe can be written as $B_r=-(\mu_0 r_s I_s/4R_{ax}r_p^2)\cos\theta$, where I_s is the island current, r_s is the minor radius of the island, and r_p is the minor radius of the magnetic probe. Since the estimated magnetic field is 10 % less than the observed one and the observed phase is as is

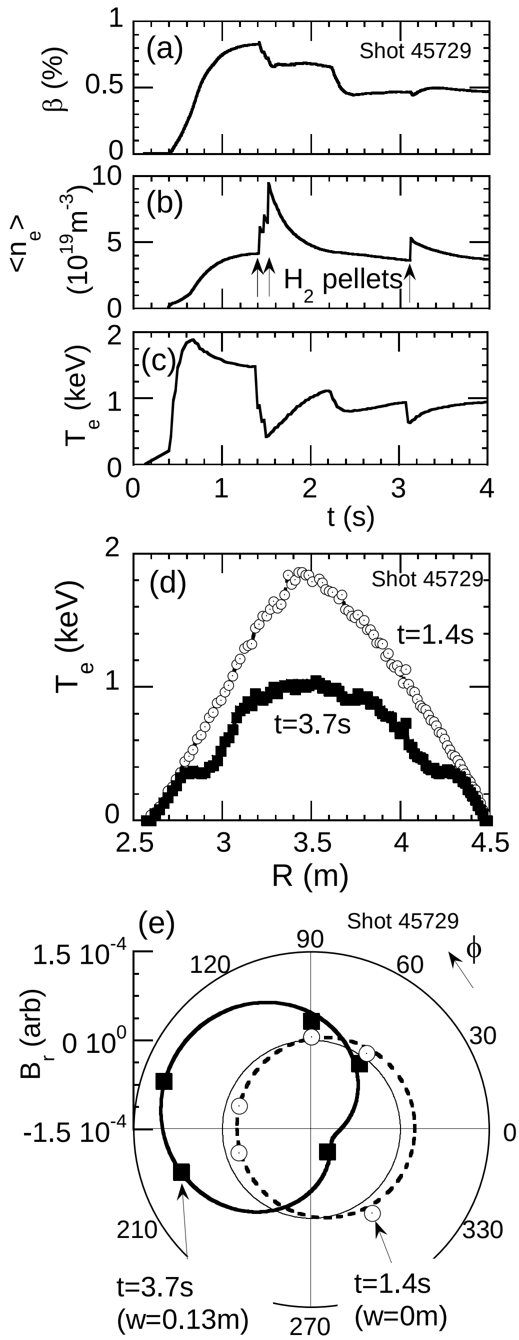

FIG.6. Time evolution of (a) beta, (b) averaged electron density, (c) temperature, (d) temperature profile, (e) the polar plot of B_r versus toroidal angle in case of R_{ax}=3.53 m without the LID field. Closed lines indicate the (1,1) component. Circular thin solid line indicates B_r =0.

expected, it can be claimed that the amplitude and the phase of the magnetic field is consistent with the (1, 1) island current.

4.2. Calculation of Pfirsch-Schlüter Current

The Pfirsch-Schlüter current is related to the beta and it may have an m=1 component. It can be obtained by the equilibrium calculation. The ‘HINT’ code [9] is useful for calculating the 3-dimensional magneto-hydrodynamic (MHD) equilibrium of a high beta plasma with a magnetic island structure. The result of a calculation using the ‘HINT’ code shows that the ‘healing’ of a high m island is obtained due to the Pfirsch-Schlüter current. However, a clear ‘healing’ of a (1, 1) island has not been obtained. So the ‘healing’ cannot be explained by the Pfirsch-Schlüter current only.

5. Discussion

There are threshold and bi-stable conditions for the generation of island. In the case of R_{ax}=3.53 m, the magnetic island is generated by external perturbations, such as the drop of NBI heating power and the injection of hydrogen ice pellets. Once the island is generated, the width is quickly increased. In the case of R_{ax}=3.6 m, the magnetic island is generated when the threshold of the external error field surpasses the threshold. With a small excess of the threshold, the wide island is generated. However, the island that is formed by cooling plasma with ice pellet injection in the case of R_{ax}=3.6 m does not have a bi-stable feature.

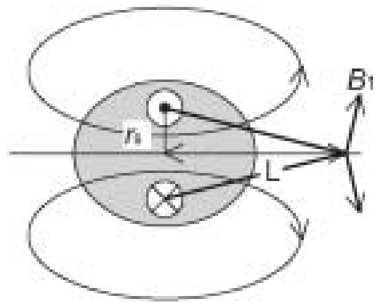

FIG.7. Schematic view of the plasma cross-section, where the m=1 current flows and generates the horizontal field.

In this experiment, we have observed that the island formation is related to the plasma parameters (T_e and the beta) and the magnetic axis position. In the case of R_{ax}=3.6 m, the island width is usually narrower than that in vacuum. In the case of low T_e, the island width is reduced as the beta is increased. In the case of low beta, the island width is reduced as the T_e is increased. Often, the island is not generated even if the island width in vacuum is as large as 20 % of the plasma minor radius. In the case of R_{ax}=3.53 m, however, the island width is wider than that in the vacuum. The magnetic axis position is related to the stability. As the R_{ax} becomes larger, the interchange mode becomes less unstable. The island width is decreased as the beta is increased. Since the interchange mode becomes less stable as the beta becomes higher, the MHD instability may not be related to the island generation, directly.

In helical systems, the plasma current is not necessary to create the magnetic island, since it is formed in the vacuum field. A basic question is whether a current flows in the plasma when ‘healing’ the magnetic island. In this experiment, the horizontal field is detected on the mid-plane when the magnetic island is generated from the small residual error field. The amplitude and phase of the observed magnetic field is consistent with the assumption that the island is generated by the island current.

It is still unknown what mechanism generates the island current in the plasma with higher T_e and lower beta. In the case of a higher beta plasma, a possible mechanism is the Pfirsch-Schlüter current, which is generated to maintain the equilibrium and is related to the beta.

Since the 3-dimensional equilibrium calculation using the 'HINT' code, which can treat the Pfirsch-Schlüter current precisely, shows that the (1, 1) island width does not change due to the beta, the reduction of island width may not be directly related to the Pfirsch-Schlüter current. The bootstrap current is another possible mechanism that is related to the beta. The bootstrap current density is higher in the region where the pressure gradient is higher. The pressure gradient is very low inside the island and is high in the vicinity of the island. Therefore the bootstrap current density may have the (1, 1) structure. A difficulty of this argument is as follows: Once the island is shrunk, the (1, 1) mode of the bootstrap current density is disappeared. So, if the bootstrap current triggers the healing, it cannot maintain the healing. Bi-stable mechanism that maintain the 'healing' has been unknown, yet.

6. Conclusion

In conclusion, the generation and the 'healing' of the magnetic island are investigated using the LID field in LHD. The generation of an island due a small error field is caused in the case of R_{ax}=3.53 m, and the 'healing' of the island is caused in the case of R_{ax}=3.6 m. The 'healing' effect is more enhanced as the beta or the T_e increases. When the island is generated from the small residual error field, the (1, 1) horizontal magnetic field is observed. This is the first observation of the evidence of the island current in helical systems. Further theoretical research is required to understand the generation of the magnetic island in helical systems. The magnetic island formation has a bi-stable state sometimes. The magnetic island dynamics should be considered in designing a helical fusion reactor, because of very high values of beta and T_e.

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