Island Dynamics in the Large-Helical-Device Plasmas

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In the Large Helical Device plasma discharges, the size of an externally imposed island with mode number ($n/m = 1/1$) decreases substantially when the plasma is collisionless ($\nu^* < \sim 1$) and the beta is finite ($> \sim 0.1\%$) at the island location. For the collisional plasmas with finite beta, on the other hand, the size of the island increases. However, there is a threshold in terms of the vacuum island size below which the island enlargement is not seen.

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A topological change of the magnetic field line is called reconnection, breaking and rejoining of the field line, which is forbidden in ideal magnetohydrodynamics. Phenomena involving reconnection occur in many plasma physics areas and have attracted much interest. In magnetic fusion devices, hot and dense plasmas are confined in the magnetic configuration with nested magnetic flux surfaces. Reconnection induced by the plasma dynamics often leads to formation of the magnetic island. In the tokamak research, the study of the island dynamics is the major topic since they are believed to influence plasma performance in the reactor grade tokamaks [1–3]. We have found interesting island dynamics in the LHD [the Large Helical Device: the largest superconducting heliotron-type fusion device, R_{ax} (major radius of the plasma axis) = 3.6 m, a (average minor radius) = 0.65 m, $B = 2.9$ T] [4–8]. Our results will provide clues for understanding island plasma behavior in toroidal confinement devices in general. They will be helpful for finding ways to avoid the detrimental effects of the island or for using its favorable effect in order to enhance plasma performance.

We reported that the island generated by the natural error field was observed as a flattening region of the electron temperature profile and the island was healed under some conditions in the LHD [9]. In the present Letter, we report the dynamics of the islands with various sizes (generated by a perturbation coil field) in the wider range of the background configurations and report the parameter space for the growth or suppression of the island in the LHD plasma discharges. Both ion and electron temperature profiles are used to estimate the width of the island. Interesting results are obtained mainly in inward shifted configurations [R_{ax} (position of the magnetic axis) = 3.5 and 3.6 m], which have a magnetic hill geometry in the entire region and have been the most commonly used for the LHD experiment because of good confinement properties. In these configurations, the rotational transform (ι: increment of the poloidal angle after one toroidal circulation of the field line) increases monotonically with radius [e.g., for the $R_{ax} = 3.6$ m configuration, $\iota/2\pi = 1$ (0.38) at ρ (the normalized radius) = 0.86 (0), and for the $R_{ax} = 3.5$ m case, $\iota/2\pi = 1$ (0.46) at $\rho = 0.91(0)$].

Figure 1 depicts the LHD configuration with an island ($n/m = 1/1$) (which resonates the field line structure at the $\iota/2\pi = 1$ surface) on the poloidal planes at two different toroidal angles (ϕ) (n and m are toroidal and poloidal mode numbers, respectively). At these locations ($\phi = 108°$ and $-18°$), electron and ion temperature profiles are measured along the R direction ($Z = 0$) by use of the Thomson scattering and the charge exchange recombination, respectively. The island size is estimated by the width of the flattening region of the temperature profile. Noting that in real space the width has a modulation of $\cos(2\theta + 10\phi)$ where θ is the poloidal angle, we define w as the island full width at the location of the O-point in terms of ρ. In our experiment, the vacuum island (island without plasma) is generated mainly by a perturbation field produced by a system of external coils and partly by error field. Its existence was directly observed by the electron beam mapping method [10]. The width of the island (w) generated by only the error field is +0.085. With the perturbation coil field, w can be changed and negative w

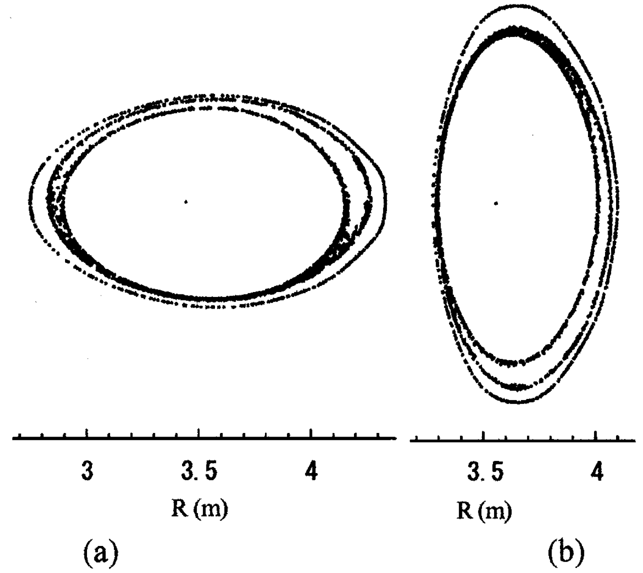

FIG. 1. Island structure in the vacuum configuration with $R_{ax} = 3.5$ m and $w_{ex} = -0.1$. (a) At $\phi = 108°$ poloidal plane [(b) At $\phi = -18°$ poloidal plane]. It is obtained by a field line tracing code.

means that its spatial phase is different by π compared with that generated by only the error field. We assume that the plasma dynamics change the island size, but not its phase (the observations do not contradict this assumption).

Figure 2 shows that island structure (local flattening) appears around $\iota/2\pi = 1$ surface ($\rho = 0.91$) in the T_i profile for the cases with w_{ex} (the width of the vacuum island) $= -0.125$. It is clearer at higher density (1.6×10^{19} m^{-3}) than at the low density (1.1×10^{19} m^{-3}). For

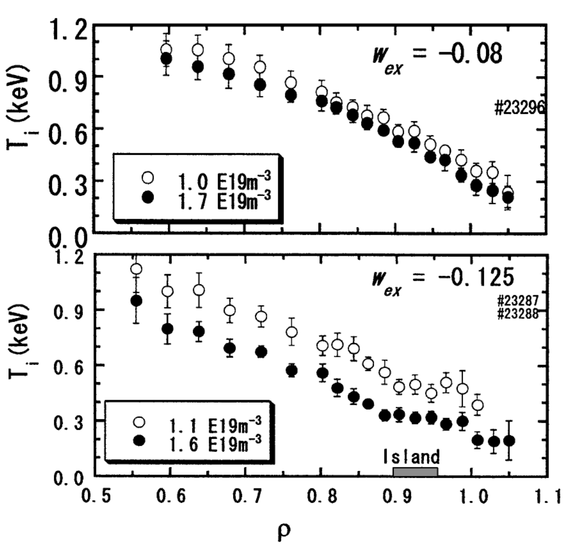

FIG. 2. The ion temperature profiles are shown for two different vacuum island widths ($w_{ex} = -0.08, w_{ex} = -0.125$). The ion temperature is measured by charge exchanged recombination method. ($B = 1.59$ T, $R_{ax} = 3.5$ m, $P_{beam} = 2.66$ MW).

the case with smaller w_{ex} ($= -0.08$), no flattening occurs, demonstrating that some island suppression mechanism exists.

Figure 3 shows the parameter space for the island suppression for a case ($R_{ax} = 3.6$ m, $w_{ex} = +0.085, B = 2.8$ T), We believe that temperature and density at the $\iota/2\pi = 1$ surface are important parameters for the island suppression and growth. The points (○) correspond to the cases with an undetected island (which means that $|w| < 0.5|w_{ex}|$), and the points (●) corresponds to those with a clear island with $w \approx w_{ex}$. Suppression of the island occurs in the lower density and high electron temperature region (region II). Instead of electron temperature and density, it may be more appropriate to use the dimensionless quantities β and ν^* $[= \nu_e(2\pi/\iota)](R/v_e^{\rm th}) \times (Z_{\rm eff}/\varepsilon^{3/2})]$ at $\iota/2\pi = 1$. The parameter space for clear suppression of the island is $\nu^* < 1.7$ and $\beta > 0.09\%$. We also studied another case [$R_{ax} = 3.5$ m, $w_{ex} = -0.125, B = 1.59$ T)] and found that the parameter space for the suppression was $\nu^* < 1.4$ and $\beta > 0.05\%$, similar to the Fig. 3 case. For low β plasma (regions I and IV), the island sizes are close to those of the vacuum island, as expected. Even though a more complete parametric study for the island behavior needs to be done, data obtained thus far show that the collisionless ($\nu^* < 1$) and finite β ($>0.1\%$) plasma suppresses the island. On the other hand, a significant enlargement of the island ($|w| \geq 2|w_{ex}|$) occurs when the plasma parameter is located far right in the region III, e.g., $\nu^* = 4, \beta = 0.15\%$, as described in Fig. 4.

Figure 4(a) shows that, when the density is ramped up slowly by gas puffing, the stored energy (W_p) initially increases and nearly saturates and, at $t = 1.6$ s, a transition takes place from a normal state to an equilibrium with a large island. The electron temperature profiles before and after the transition are shown in Fig. 4(b). After the transition, a clear local flattening of the electron

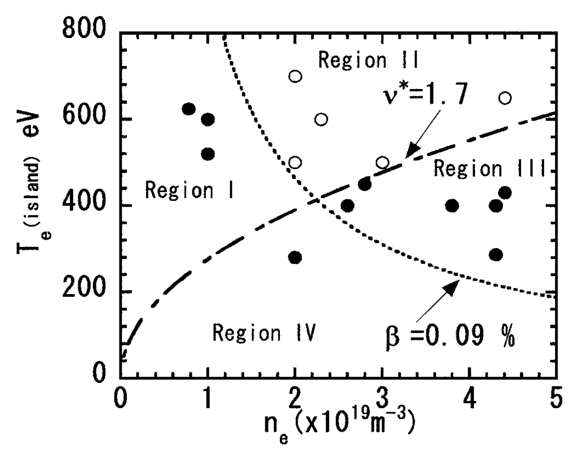

FIG. 3. Parameter space ($T_{e({\rm island})}, n$) for island suppression for a case ($w_{ex} = +0.085, B = 2.5$–2.75 T, $R_{ax} = 3.6$ m). ○: no island, ●: island with $w \sim w_{ex}$.

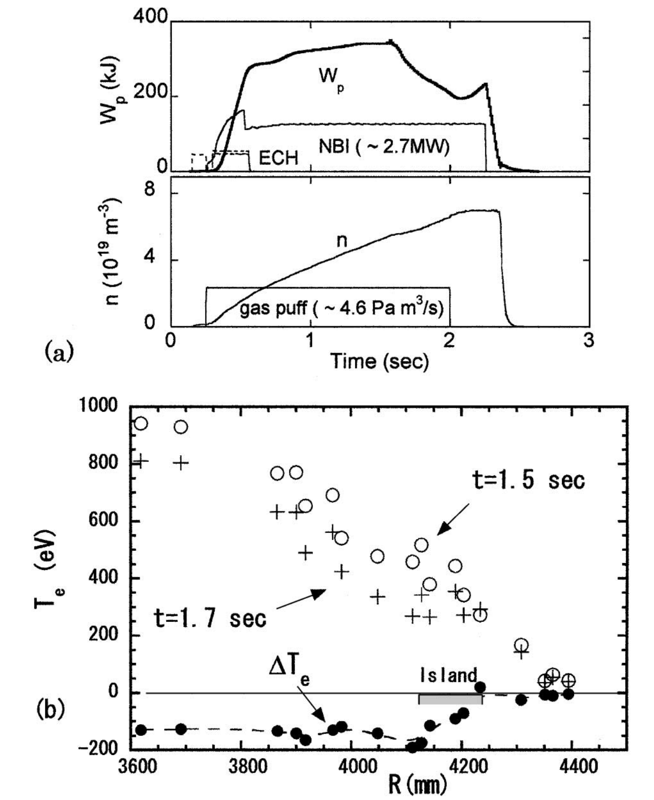

FIG. 4. (a) Time evolution of the stored energy (W_p) and the average density (n) in an LHD discharge ($R_{ax} = 3.5$ m, $B = 2.8$ T) shows a transition from a normal state to an equilibrium with a large island. (b) The electron temperature profiles before ($t = 1.5$ s) and after ($t = 1.7$ s) the transition. The typical error bar in these temperature measurements is 10%. The temperature difference between two times, $\Delta T_e = T_e(t = 1.7 \text{ s}) - T_e(t = 1.5 \text{ s})$, is also plotted to make the existence of the island clear.

temperature profile at $\iota/2\pi = 1$ ($R = 4.20$ and 2.85 m) appears and leads to a drop ($\Delta T_e \sim -150$ eV) in the temperature in the core, resulting in a significant reduction in W_p. The flattening region of ~120 mm in R, corresponding to $w = 0.12$ is much wider than that in the vacuum configuration (~40 mm in R). The edge profile beyond the island ($R > 4.25$ m), however, remains almost unchanged ($\Delta T_e \sim 0$).

In Fig. 5, W_p is plotted as a function of density for various w_{ex} (vacuum island width). For $w_{ex} = +0.045$, no clear island is detected at any density. The W_p scales approximately as $(n)^{1/2}$, but saturates at higher density, typical of the density dependence of W_p in LHD discharges. For $w_{ex} = -0.07$, the island starts to appear when the density exceeds a threshold value, and at the same time W_p starts to become lower than that with $w_{ex} = +0.045$. This threshold values tends to decrease with increasing $|w_{ex}|$. For a large vacuum island ($w_{ex} = -0.11$), an island is seen at any density and the island width (w) increases significantly with density, causing a large drop in W_p. When n is below 1.5×10^{19} m^{-3}, the stored plasma energy (W_p) is insensitive to w_{ex}. Data in Figs. 4 and 5 clearly show

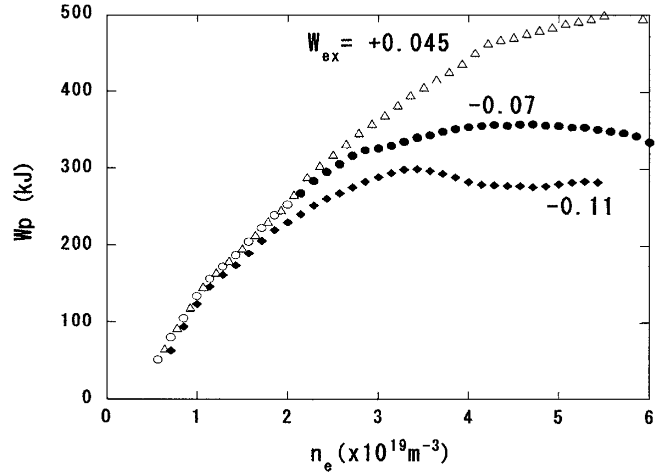

FIG. 5. The stored plasma energies (W_p) are plotted as a function of the density (n) for various vacuum island sizes ($B = 2.83$ T, $R_{ax} = 3.5$ m). For $w_{ex} = +0.045$ case (△, no island appears. For $w_{ex} = -0.07$ case, an island appears at higher density [(○: no island), (●: island)]. For $w_{ex} = -0.11$ case (◆), an island is always seen.

that, with higher n and larger w_{ex}, plasma dynamics enlarge the island, much larger than that in the vacuum configuration and, hence, the energy confinement deteriorates severely. Such an island enlargement is the strongest for the most inward shifted configuration ($R_{ax} = 3.5$ m). For $R_{ax} = 3.6$ m, this effect is much weaker and the threshold density is much higher.

In the LHD experiment, beam driven toroidal plasma current is small, ranging from -50 to 50 kA (change in $\iota/2\pi$ is less than 0.05, a small perturbation to $\iota/2\pi$ profile) and thus the plasma configuration is stable against the current driven mode (kink). Indeed, we find that the island behavior described in this Letter is not sensitive to the amplitude and polarity of the beam driven current. In the LHD configuration with present parameters, low m mode ($n/m = 1/1$) is stable theoretically and, hence, we consider the observed island dynamics as variations in stable equilibria with the island. Growth or suppression of the externally imposed island requires the plasma induced current density with an $n/m = 1/1$ mode pattern. In the tokamak tearing mode study, three driving (or suppression) mechanisms are considered, which are due to the bootstrap (BS) current, curvature driven Pfirsch-Schluter (PS) current, and the polarization current [1–3,11–14]. We examine whether these mechanisms are applicable to the LHD. In our experiment where stationary and large islands are concerned, the polarization effect can be neglected. The island full normalized with (w) is given by [15]

$$w^2 = 16(R/a)(\rho_s/ns)(b^r_{ex} + b^r_{pl})/B. \qquad (1)$$

Here ρ_s is the normalized radius of the island and s is the shear [$s = (\rho_s/t)(dt/d\rho)$]. Note that the radial component of the perturbed magnetic field is the sum of b^r_{ex} (that of the external perturbed field) and b^r_{pl} (that of the plasma induced perturbed field). Similarly, the island width generated only by the external field (w_{ex}) is obtained by making $b^r_{pl} = 0$ in Eq. (1). Eliminating b^r_{ex} in favor of w_{ex} gives

$$w = (w_{ex}^2 + w_{pl}^2/4)^{1/2} + w_{pl}/2, \quad (2)$$

where w_{pl} is defined as

$$w_{pl} = -16(R/a)(\rho_s/ns)(b^r_{pl}/Bw). \quad (3)$$

We now assume that the plasma induced perturbing field (b^r_{pl}) is proportional to the island width (w), and thus w_{pl} is independent of w. This is valid for a BS current induced island and a PS current induced island and thus w_{pl} (the width without external perturbation) $= w_{pl}^{boot} + w_{pl}^{PS}$. The island width ($w_{pl}^{boot}$) due to the BS current is given by

$$w_{pl}^{boot} \approx -3(R/a)(\rho_s/ns)(\mu_o j_{bs} a/B), \quad (4)$$

where j_{bs} is the BS current density without the island perturbation [2], For the LHD ($s > 0$) with positive j_{bs} (i.e., BS current flows in such a way to increase the rotational transform), w_{pl}^{boot} is negative, making the island smaller. The observed parameter space for the island suppression ($\upsilon^* < 1, \beta > 0.1\%$) seems to favor the BS current suppression model since high BS current density requires high β and low ν^*. From Eqs. (2)–(4), reduction of the island width down to $w_{ex}/2$ requires $w_{pl}^{boot} \sim -1.5 w_{ex}$ (we assume that $|w_{pl}^{PS}| \ll |w_{pl}^{boot}|$) and the required normalized BS current density ($\mu J_{bs} a/B$) around the $\iota/2\pi = 1$ surface is $\sim 0.17 w_{ex}$ for the LHD parameters [from Eq. (4)]. We observed a total BS current of $\sim$30 kA at $B = 2.8$ T, which corresponds to the normalized BS current density averaged over the poloidal cross section $\langle \mu J_{bs} a/B \rangle$ of 0.8×10^{-2}. Since the island with $w_{ex} = 0.1$ is suppressed, $\mu J_{bs} a/B$ needs to be greater than 0.017, twice the average value, which is plausible. Numerical estimation of the BS current density predicts that, for the LHD configuration with $R_{ax} \sim 3.5$–3.6 m, the BS current density is positive in the core. But it is predicted to be small and even slightly negative around the $\iota/2\pi = 1$ surface due to higher harmonics components of the magnetic field (a very subtle effect) [16] (direct experimental measurement of the BS current density profile is highly desirable). Or it may be an indication that some other mechanisms are operational, such as mechanisms due to the global effect [17] or MHD instability peculiar to the $M = 1$ mode.

The size of the island tends to be increased by the PS current effect in the magnetic hill geometry. The width (w_{pl}^{PS}) due to the PS current is positive and is given by

$$w_{pl}^{PS} \sim 2\rho_s(E + F)/m, \quad (5)$$

where $E + F$ is the Mercier stability parameter, which is proportional to the gradient of local beta and also the average curvature [11–14]. The ratio of $w_{pl}^{PS}/w_{pl}^{boot}$ is proportional to $(r_s/R)^{1/2}(RK)/s$ and it is insensitive to the plasma parameter for the plasmas ($\nu^* < 1$) where K is the average curvature of the field line. The PS current enlargement model agrees with the observation qualitatively. It is consistent with a fact that the enlargement of the island appears more easily with decreasing R_{ax}, i.e., stronger hill geometry and, hence, larger $E + F$. From Eq. (2), doubling the island size ($w = 2w_{ex}$) requires $w_{pl}^{PS} \sim 1.5 w_{ex}$. For this case (parabolic pressure profile with central beta 1% in the 3.5 m configuration), the value of w_{pl}^{PS} is 0.26, large enough for enlargement of the island with $w_{ex} = 0.1$.

Experimentally, island enlargement does not occur when $|w_{ex} a| < 3$ cm for $R_{ax} = 3.5$ m. When the vacuum island is small, perpendicular transport dominates over parallel transport in the island region and flattening of the pressured profile and, hence, PS current amplification of the island would not occur. For typical LHD edge parameters, the minimum island size for flattening is expected to be $\sim$2 cm.

In summary, we have found that collisionless finite beta LHD plasmas reduce the island size with $n/m = 1/1$, a very favorable plasma effect, and the collisional, finite beta plasmas, on the other hand, enlarge the externally imposed island significantly.

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