Transition to detached plasma established by amplified resonant magnetic perturbation in LHD

Y. Narushima1,2, M. Kobayashi1,2, H. Tanaka3, S. Sakakibara1,2, Y. Takemura1, K. Y. Watanabe1, S. Ohdachi1,2, Y. Suzuki1,2, S. Masuzaki1, N. Ohno3, F. Castejón4, D. López-Bruna4, and the LHD Experiment Group

1 National Institute for Fusion Science Oroshi-cho 322-6, Toki 509-5292 Japan
2 SOKENDAI Oroshi-cho 322-6, Toki-City, Gifu, 509-5292 Japan
3 Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan
4 Laboratorio Nacional de Fusión. CIEMAT, Avenida Complutense 42, 28040, Madrid, Spain

1. Introduction

Detached plasmas are required for mitigation of the heat load on the divertor, which is a critical issue for realizing the magnetically confined fusion reactor. Therefore, externally controlled methods, such as gas puffing in the divertor region, have been studied in order to maintain the detached plasma. A resonant magnetic perturbation (RMP) is utilized to establish detached plasmas in the LHD experiments [1 - 3]. The LHD is the heliotron device equipped with the RMP coils, which can produce a magnetic island with the Fourier mode of $m/n = 1/1$. (Here $m/n$ is the poloidal/toroidal Fourier mode number.) Recently, the relationship between the behaviour of the perturbed magnetic field and the condition of the transition for the detached state has been investigated [4]. The purpose of this study is to clarify the mechanism for forming the detached state by the RMP.

2. Detached plasmas produced by RMP

2.1 Transition to detached state under imposing RMP field

In a previous study, a RMP has been imposed to obtain detached plasmas, in which the following facts have been found empirically. A

Fig.1 Discharge with transition to the detached state at $t = 4.6$ s. RMP is imposed during the discharge. The time evolution of (a) ion-saturation current on divertor, (b) electron temperature at two positions, (c) electron density, (d) amplitude of effective perturbed field $\Delta\Phi_{\text{eff}}$, and (e) phase $\Delta\theta_{\text{eff}}$. 

(a) $I_i[A]$  
(b) $T_e[\text{keV}]$  
(c) $n_e[10^{20} \text{ m}^{-3}]$  
(d) $\Delta\Phi_{\text{eff}}[10^4 \text{ Wb}]$  
(e) $\Delta\theta_{\text{eff}}[\pi \text{ rad}]$ 

Detach
$R = 3.9m$
$R = 4.6m$

Threshold
large RMP amplitude seems to be necessary to obtain detached plasmas. However, the mechanism to determine the threshold of RMP has not been found. As reported in Ref. [3], even though the imposed RMP amplitudes are the same, the timings of the transition in each discharge are not. Figure 1 shows the typical plasma discharge with the transition to the detached state at $t = 4.6$ s, imposing RMP. When the plasma enters the detached state, the ion-saturation current on the divertor ($I_{\text{sat}}$) suddenly drops (Fig. 1 (a)) and the electron temperature ($T_e$) at the peripheral region ($R = 4.6$ m) decreases whereas the central electron temperature at $R = 3.9$ m is maintained at around 1keV (Fig. 1 (b)) despite the electron density ($n_e$) continues increasing during the discharge (Fig. 1 (c)). The profiles of $T_e$ and $n_e$ in the attached and detached plasmas are plotted in Fig.2, showing an improvement of confinement in the detached phase. (See Fig. 3 in Ref. [1].) The transition to the detached state occurs when the amplitude of the perturbed field of $m/n = 1/1$ ($\Delta \Phi_{\text{eff}}$) increases to reach a certain value (Fig. 1 (d)). Here, the perturbed field ($\Delta \Phi_{\text{eff}}$) includes the RMP field plus the intrinsic error field (hereafter called the “vacuum perturbed field” $\Delta \Phi_{\text{ext}}$), and also the plasma response field. The phase of the perturbed field ($\Delta \theta_{\text{eff}}$) does not change while maintained at $\Delta \theta_{\text{eff}} \sim 0$, which means that the perturbed field does not rotate. The RMP perturbation is modified by the plasma response field, so the perturbed flux is given by $\Delta \Phi_{\text{eff}}$ during the plasma discharge. This magnitude evolves during the discharge and increases suddenly during the transition to the detached state (Fig. 1 (d)).

2.2 Relationship between the perturbed magnetic field and the RMP field

As shown in Fig.1, we have found that there is a threshold of $\Delta \Phi_{\text{eff}}$ for the transition to detached plasma under the condition of keeping constant the RMP-coil current. It should be noted that the amplitude of the perturbed field ($\Delta \Phi_{\text{eff}}$) brings the information of the actual magnetic structure, which may suggest that the detached plasma can be realized depending on the structure of the magnetic configuration. In other words, the transition to the detached state may occur when the perturbed field ($\Delta \Phi_{\text{eff}}$) reaches a certain value for the same RMP. We have attempted to obtain detached plasmas under some values of the RMP coil current.
$I_{\text{RMP}}$ in order to investigate the dependency of the threshold of the $\Delta \Phi_{\text{eff}}$ on the RMP amplitude. In Fig. 3, the detached (attached) state is indicated by open (closed) circles and the gray solid line indicates the $\Delta \Phi_{\text{eff}} = \Delta \Phi_{\text{ext}}$, given by the RMP and the intrinsic error field. The detached state is obtained in the higher $I_{\text{RMP}}$ (> 1.9kA) cases whereas it is not realized in the lower $I_{\text{RMP}}$ (= 1.5kA) cases. This behaviour, in which high RMP is required for the detachment, has been found in previous studies. Thresholds of $\Delta \Phi_{\text{eff}}$ for $I_{\text{RMP}} = 2$, 2.5, and 3 kA are estimated as $\Delta \Phi_{\text{eff}} = 3.8$, 5.3, and $6.4 \times 10^{-4}$ Wb, respectively, and the threshold of the $\Delta \Phi_{\text{eff}}$ increases with $I_{\text{RMP}}$. If the structure of the magnetic field determined univocally the condition to obtain the detached state, the threshold of the $\Delta \Phi_{\text{eff}}$ should be constant regardless of the RMP coil current $I_{\text{RMP}}$. However, these experimental facts mean that the structure of the magnetic field is not a sufficient condition for obtaining detached plasmas.

3. Discussion and Summary

Before entering into the discussion, the experimental facts are listed. First, high RMP ($I_{\text{RMP}} > 1.9kA$) is required to obtain detached plasmas (previous studies). Second, the perturbed field $\Delta \Phi_{\text{eff}}$ increases until the transition to the detached state (Fig. 1 (d)). Third, the threshold of the $\Delta \Phi_{\text{eff}}$ for the transition is not constant but increases with the RMP coil current $I_{\text{RMP}}$ (Fig. 3). The detached state is obtained when the $\Delta \Phi_{\text{eff}}$ becomes larger than the $\Delta \Phi_{\text{ext}}$ (open circles in Fig. 3), which implies that certain mechanisms amplify the RMP. The amplification of the perturbed field in the
detached plasma can be thought to be the growth of the magnetic island from the viewpoint of the magnetic island dynamics. It has been shown that the growth of the magnetic island is realized for low beta and high collisionality plasmas [5]. Figure 4 plots the beta and the collisionality estimated at \( R = 4.6 \) m (at the magnetic island). The detached plasmas (open circles) are distributed at the lower beta and the higher collisionality region, and vice versa. In the case of the \( I_{RMP} = 1.5 \) kA (black closed circles in Fig. 4), plasmas lie at the higher-\( \beta \) and the lower \( \nu \) region, and do not enter the “Detached” region. These behaviours correspond to those of the magnetic island: detachment is got when the island is wider enough: it has been found that the poloidal flow decreases and the RMP penetrates to make the magnetic island larger. For detached plasmas, it can be deduced that a similar mechanism occurs. Namely, even though the magnetic configuration is not the same, the detached plasma can be realized by a condition related to the poloidal flow. Looking at the plasmas for the \( I_{RMP} = 1.5 \) kA in Fig. 3 and Fig. 4, one can imagine that the detachment might be obtained if the plasma parameters enter the “Detached” region which leads to the increase in the perturbed field \( \Delta \Phi_{\text{eff}}, \) exceeding \( \Delta \Phi_{\text{ext}}. \)

4. Conclusions

The mechanism to form the detached state by the RMP in LHD is studied from the viewpoint of the magnetic structure in the peripheral region. The perturbed magnetic field is amplified by the plasma response field and increases until the detached state is realized. The threshold of the perturbed field is not constant and depends on the amplitude of the RMP. These experimental facts imply that the detached plasma does not depend only on the magnetic configuration structure itself. Recalling the behavior of the magnetic island, it can be deduced that the magnetic island is wider than the vacuum island when the detached state is obtained, and, hence, the detached states are realized in the lower-beta and higher-collisionality region.

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References