Structure of resonant magnetic perturbation in LHD detached plasma

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1. Introduction

Reduction of the heat load on a divertor is an urgent issue for realizing the magnetically confined fusion reactors. To maintain the detached plasma, externally controlled methods such as gas puffing in the divertor region have been studied. In the LHD experiments, a resonant magnetic perturbation (RMP) is utilized to establish detached plasmas [1, 2]. It was reported that the finite *plasma response field* (PRF) is detected and shows a significant critical value of the phase difference, $\Delta\theta_{pl}$ (defined as the phase difference between the RMP and the PRF), to establish the detached state as shown in fig. 1. The behaviour of $\Delta\theta_{pl}$ was discussed in detail in Ref. [3], but the amplitude of the PRF $\Delta\Phi_{pl}$ was not dealt with, and the exact structure of the magnetic island has not been investigated in detail.

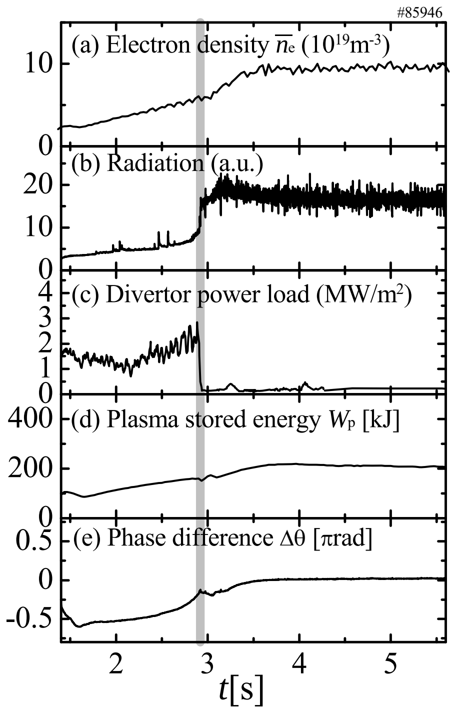

Fig.1 Time evolution of (a) line averaged electron density, (b) radiation, (c) divertor power load, (d) plasma stored energy and (e) phase difference. Detached state is established at $t \sim 2.9$s indicated by grey bold line. From Ref. [3]

2. Experimental setup and configuration of RMP

The LHD heliotron is equipped with RMP coils, which can impose an external perturbed field with the Fourier mode of $m/n = 1/1$ (here m/n is the poloidal/toroidal mode). The phase of the RMP in the laboratory frame can be varied of 36° in the toroidal direction, as shown in fig. 2. The O-point of the magnetic island is set at the outer board in the equatorial plane at the port named '7-O' in fig. 2 (a), whereas it is set at '6-O' in fig. 2 (b). Hereafter, each of the two configurations

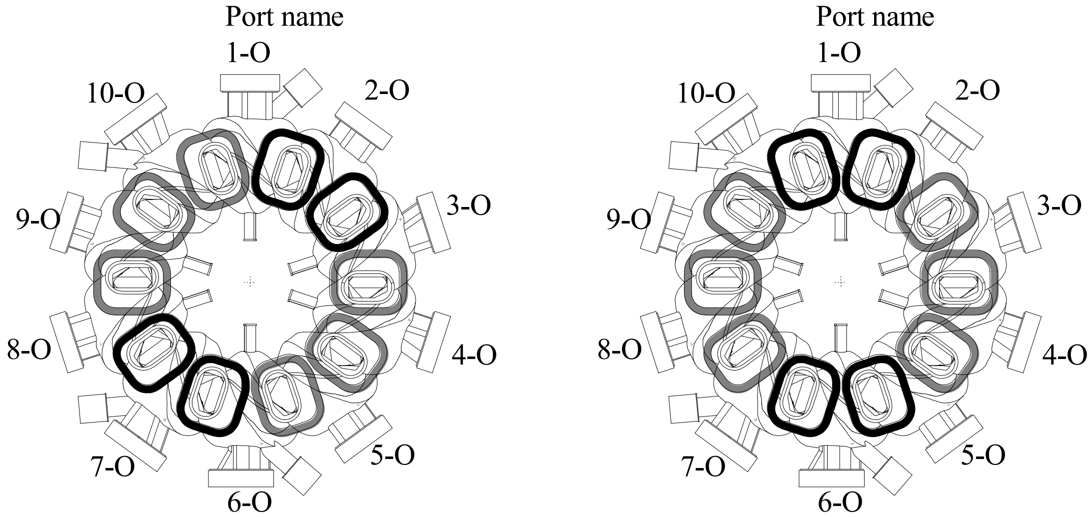

Fig.2 Top view of vacuum vessel and resonant magnetic perturbation coil system of LHD. Coils for m/n = 1/1 are colored in black. Coils for m/n = 2/1 are colored in grey. (a) The O-point of the magnetic island is set at the equatorial plane at the port of 7-O called '7-O configuration'. (b) The O-point of the magnetic island is set at the equatorial plane at the port of 6-O called '6-O configuration'.

in fig. 2 (a) and (b) are called '7-O configuration' and '6-O configuration', respectively. We have to take into account the intrinsic error field except for the PRF and RMP. The intrinsic error field comes from the misalignment of the coils in the LHD. The 'vacuum perturbed field' is composed by the RMP and the intrinsic error field. Therefore, the structure of the 'vacuum perturbed field' changes when the phase of RMP is varied.

3. Experimental result

3. 1. Behaviour of the plasma response field and effective perturbed field

The typical discharges with the transition from the attached state to the detached one are shown in fig. 3. It is found that the waveforms of the $\Delta\Phi_{pl}$ show different behaviours before the transition depending on the RMP configuration (fig. 3 (b), (g)). Under the '7-O configuration' case, $\Delta\Phi_{pl}$ continues to increase until the transition (fig. 3 (b)), whereas it decreases just before the transition after the increase in $\Delta\Phi_{pl}$ until t = 4.4 [s] in the '6-O configuration' case (fig. 3 (g)). The critical values of the $\Delta\theta_{pl}$ are different in each

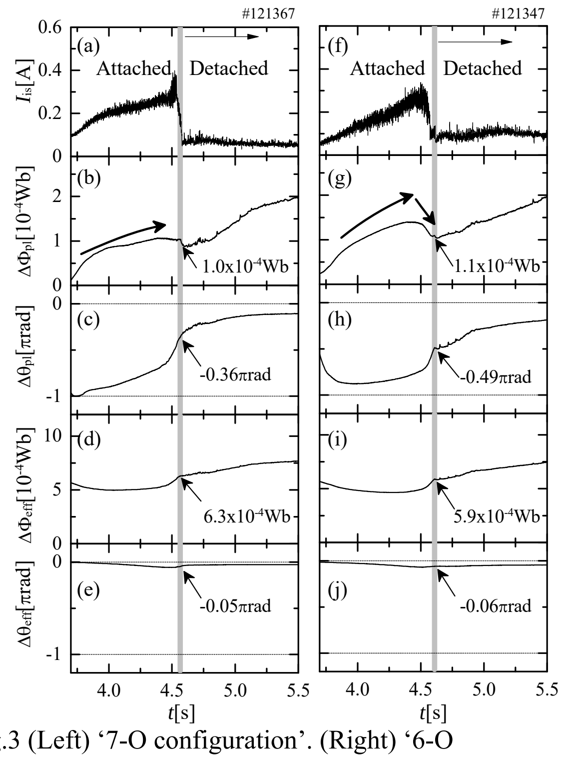

Fig.3 (Left) '7-O configuration'. (Right) '6-O configuration'. Waveforms of (a, f) ion-saturation current on divertor, (b, g) amplitude of plasma response field (PRF), (c, h) phase of PRF. Waveforms of (d, i) amplitude of effective perturbed field (EPF), (e, j) phase of EPF.

case. The $\Delta\theta_{pl}$ are $\Delta\theta_{pl}$ = -0.36 (πrad) (7-O (fig. 3 (c))) and $\Delta\theta_{pl}$ = -0.49 (πrad) (6-O (fig. 3 (h))), respectively. 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, the PRF and the intrinsic error field. To determine the exact island structure, the *effective perturbed field* (EPF), obtained by adding those fields should be adopted. We estimated the amplitude ($\Delta\Phi_{eff}$) and the phase ($\Delta\theta_{eff}$) of the EPF. The $\Delta\theta_{eff}$ means the phase difference between the EPF and perturbed field excluding the PRF. Figures 3 (d), (e), (i) and (j) show the waveforms of the $\Delta\Phi_{eff}$ and the $\Delta\theta_{eff}$. When the $\Delta\Phi_{eff}$ increases over a critical value $\Delta\Phi_{eff} \sim 6\times10^{-4}$ Wb corresponding to the perturbed field excluding the PRF, the plasma enters into the detached state. At that time, the phase of EPF maintains $\Delta\theta_{eff} \sim 0$. The waveforms of the EPF in both cases of '7-O' and '6-O' configurations are similar, which means that the magnetic island shows a common behaviour in the plasma discharge having the detached transition whereas those of the PRF are different in each RMP configuration. These experimental observations mean that the detached state is accompanied by the amplification of the perturbed field leading to the enlargement of the magnetic island without the phase shift from externally imposed perturbed field.

3. 2. Structure of resonant magnetic perturbation in LHD detached plasma

The electron temperature profiles before and after the transition are shown in fig. 4. At the inboard-side of the T_e profiles, significant local flattening region can be seen at $R \sim 3.1$ m. In the Poincaré plot, the magnetic islands are embedded in the regions which seem to be a stochastic structure that has been coloured in grey (fig. 4 (b) (d)). Even though it is difficult to see the island structure, the O-point of the magnetic island is indicated by the letter 'O'.

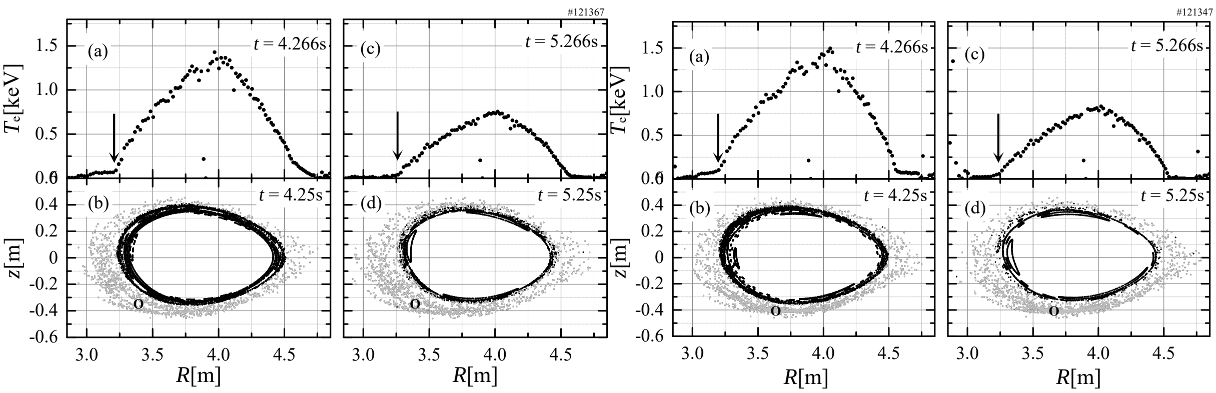

Fig. 4 (Left) '7-O configuration'. (Right) '6-O configuration'. Electron temperature profiles (a) before and (c) after the transition. Poincare plots calculated using EPF are also shown in (b) before and (d) after the transition. The magnetic island structure is embedded in the region colored grey. The O-point of the magnetic island is indicated by letter 'O'.

Before the transition, the foot-points indicated by an arrow in fig. 4 (a) lie at R = 3.2 m, and they move to R = 3.25 m after the transition (fig. 4 (c)). These experimental observations correspond to the behaviour of the EPF, in which the magnetic island structure becomes large when the plasma enters into the detached state. Common behaviours of the T_e profiles are observed in both RMP configurations.

4. Summary

The behaviours of the perturbed magnetic fields including the RMP, the intrinsic error field, and the PRF are studied in the discharge with the transition from the attached state to the detached state. Regarding the PRF, the waveforms of the amplitude of the PRF are different in each RMP configuration, and the thresholds of the phase of the PRF are also different. Taking into account the EPF including the RMP, the intrinsic error field, and the PRF, common behaviours in each configuration are observed. When the $\Delta\Phi_{eff}$ increases over a critical value, the plasma enters into the detached state maintaining the phase of EPF $\Delta\theta_{eff} \sim 0$. The shape of the magnetic island can be estimated by the EPF. The phase of the magnetic island barely shifts during the transition. Before the transition, the width of the magnetic island is smaller than the vacuum magnetic island which does not include the plasma response field. When the plasma enters into the detached state, the width of the magnetic island becomes larger than that of the vacuum island. These island behaviours are also confirmed by the electron temperature profiles. The plasma response field enhances the externally imposed perturbed field (RMP and intrinsic error field). The resulting effective perturbed field modifies the magnetic field structure around the peripheral region when the detached plasmas are realised.

Acknowledgement

This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research(C) (15K06649). This work was also supported by the budget ULPP014 of NIFS. This work has been partially supported by the Spanish Ministry of Economy and Competitively, grant ENE2014-52174-P

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