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# Effect of Magnetic Shear and Resonant Magnetic Field on low-*m* mode in LHD

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## 1. Introduction

An understanding of characteristics of ideal and resistive pressure driven instabilities in net current-free plasmas is one of major key issues for realization of high-beta plasma production. In standard configuration of Large Helical Device (LHD), the $m/n = 1/1$ mode where the resonance is located in periphery with magnetic hill and strong magnetic shear has been enhanced with increasing beta and pressure gradient. The clear dependence of the mode on a magnetic Reynolds number has been found out, and it is close to that of growth rate predicted by linear theory of resistive interchange mode [1]. On the other hand, when the magnetic shear is decreased by controlling magnetic configuration and/or by positive plasma currents increasing rotational transform, non-rotating $m/n = 1/1$ mode appears and abruptly grows instead of the rotating resistive $m/n = 1/1$ mode. The mode causes the minor collapse in the core region and the plasma energy loss reaches more than 50 % in case of the lowest magnetic shear configuration. It was found out that the mode clearly limits the operation regime of LHD, which is qualitatively consistent with predicted ideal stability boundary [1].

In this study, the control of non-rotating $m/n = 1/1$ mode was attempted by means of an external magnetic field including the $m/n = 1/1$ component mainly. Usually, the mode has no rotation frequency and grows at the place where a natural error filed in LHD exists. The external coils are equipped in LHD in order to compensate the error field and/or to apply the local island divertor system [2]. The effect of strength of external field on the activity of the mode was investigated through the experiments.

## 2. Magnetic Configuration

Figure 1 shows the changes of magnetic shear and $V''$ on the $\iota/2\pi = 1$ surface as a function of $\gamma_c$, where $\gamma_c$ is the pitch parameter of helical coil, which is defined as $\gamma_c = 5a_c/R_0$ in the LHD case [3], and $V$ is a volume of a magnetic flux tube. The region with $V'' > 0$ corresponds to the magnetic hill. The vacuum magnetic axis $R_{ax}$ is set at 3.6 m. The central rotational transforms at the $\gamma_c$ = 1.254 and 1.33 are 0.38 and 0.73, respectively. When the $\gamma_c$ is decreased from 1.254 (standard) to 1.13, the magnetic shear gradually reduces from 2.8 to 1. Although $V''$ reduces because the $\iota/2\pi$ = 1 surface moves to inner region due to an increment of central rotational transform, the reduction of the magnetic shear brings the plasma close to the ideal stability boundary.

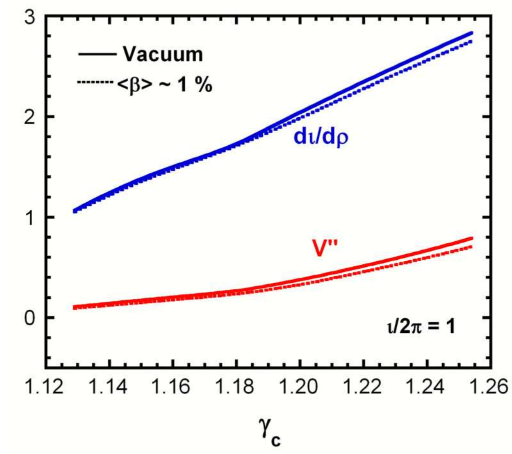


Fig 1. Changes of $d\iota/d\rho$ and $V''$ on the $\iota/2\pi$ = 1 surface as a function of $\gamma_c$

In the $\gamma_c$ = 1.13 case, which is the target of this experimental study, the magnetic shear and $V''$ hardly change when $\langle\beta\rangle$ increases to 1 % because finite-$\beta$ effects such as Shafranov shift are small compared with the $\gamma_c$ = 1.254 case. The highest-$\beta$ plasma with 4.5 % was achieved in the configuration with $\gamma_c$ = 1.20, and then there is no excitation of the large $m/n$ = 1/1 mode.

## 3. Experimental Results

Typical NBI discharge in the configuration with $R_{ax}$ = 3.6 m, $B_t$ = 0.9 T and $\gamma_c$ = 1.13 is shown in Fig.2. The NBI in the co- direction was applied here and the port-through power was 2.9 MW. The $\langle\beta_{dia}\rangle$ increased with an electron density ramp-up, and it started to decrease from 0.57 s. The strength of the radial component of the $m/n$ = 1/1 mode, $b_{r\text{-}1/1}/B_t$,

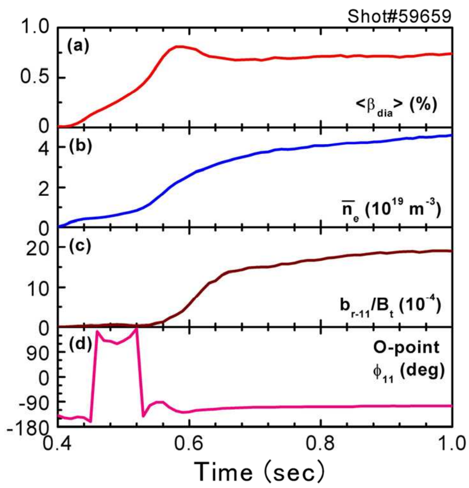


Fig 2. Typical discharge in the configuration with $\gamma_c$ = 1.13.

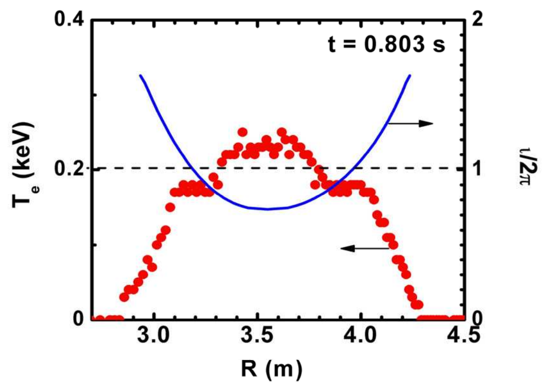


Fig 3. Profiles of electron temperature and rotational transform at 0.803 s in Fig.2 discharge.

on the $\iota/2\pi$ = 1 surface, which was identified by magnetic measurements, non-linearly increase from 0.53 s despite no external field. Figure 2(d) shows the spatial location of the $m/n$ = 1/1 mode, and $\phi_{11}$ is toroidal angle where the O-point of the $m/n$ = 1/1 island is located at poloidal angle $\theta$ = 0 and $z$ = 0. The mode grew and saturated at the specific location with $\phi_{11}$ ~ -120°. Figure 3 shows the $T_e$ and $\iota/2\pi$ profiles at 0.803 s in this discharge. The $T_e$ profile was measured with Thomson scattering at $\phi$ = -18°. The $T_e$ profile has a flattening structure around $\iota/2\pi$ = 1 resonant surface and the location of the island predicted by the profile structure is consistent with the results of magnetic measurements. The previous surface mapping experiments indicates that LHD has the $m/n$ = 1/1 natural island and the O-point is located between $\phi$=-90° and -126°. Thus, it is predicted that the growth and saturation of the mode are deeply related with that of the static magnetic island.

In this experiment, the external magnetic field with the $m/n$ = 1/1 component was added to the same plasmas as fig.2 discharge, and the normalized coil current $I_{LID}/B_t$ was changed from -833 to 833 kA/T. The positive coil current produces the 1/1 island at which the O-point is located at $\phi$ = -126°. The positive current extends the width of the natural island, whereas the negative current almost cancels it. The dependence of $I_{LID}/B_t$ on plasma parameters and the activity of $m/n$ = 1/1 mode under the condition with constant $n_e$ are shown in fig.4. The net plasma currents were very small in any discharge. Then the observed modes almost saturated. When the positive $I_{LID}/B_t$ was increased, $b_{r\text{-}11}/B_t$ gradually increased and the location approached that of given $m/n$ = 1/1 island as shown in Fig.4(d). The $<\beta_{dia}>$ gradually decreases due to the extension of the island width.

On the other hand, when the negative $I_{LID}/B_t$ was applied, the amplitude of the mode abruptly reduced with the increase in $|I_{LID}/B_t|$ and had the minimum at -278 A/T. Then $<\beta_{dia}>$ recovered and had the maximum value. The

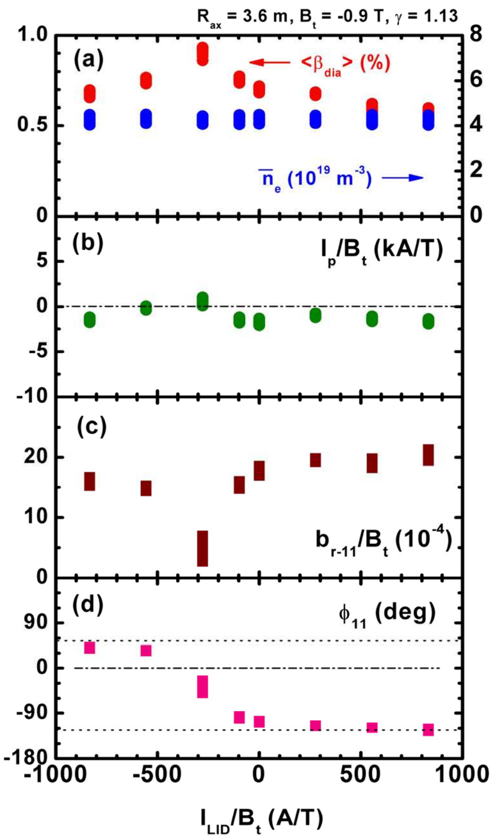


Fig.4 Changes of (a) $<\beta_{dia}>$, $n_e$, (b) $I_p/B_t$, (c) $b_{r\text{-}11}/B_t$ and (d) $\phi_{11}$ as a function of $I_{LID}/B_t$.

amplitude of the mode increased again when $I_{LID}/B_t$ < -278 A/T. The location of the island gradually rotated in the opposite direction and approached the position of given 1/1 island when negative $I_{LID}/B_t$ increased. Thus, the results suggests that it is possible to completely stabilize non-rotating $m/n$ = 1/1 mode by means of moderate external magnetic field. The saturation level of the mode strongly depends on given island width.

**4. Discussion and Summary**

It was found out through the experiments that the excitation and saturation of non-rotating m/n = 1/1 mode clearly depend on static magnetic island in addition to the magnetic shear. The non-linear behaviour of the non-rotating mode seems to have phenomenological similarity to that of the locked mode in tokamaks [4]. The mode appears when the magnetic shear decreases below the threshold [1]. This means that the mode non-linearly grows when the width of the static island exceeds the certain value. While resistive tearing mode is enough stable, the reduction of the magnetic shear destabilizes the ideal interchange mode and extends the width of the radial structure. From this point of view, the interaction between interchange modes and static magnetic island should be considered for understanding the mechanism of the excitation of the mode and the similarity to the locked mode. Also, the measurement of the plasma rotation around the resonance is expected to give the significant information on it.

The growth of the mode is prevented by strength of given static field, and the mode causes no major disruption. This means high controllability to the mode in fusion reactor even in case of the configuration with natural error field. The experiments indicate the possibility for complete stabilization of the mode by optimal external field.

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