MHD Characteristics in High-b Regime of the Large Helical Device

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Abstract: The highest volume averaged beta value b_t of 2.2% at B_t = 0.75 T (gas puff) and 2.4 % at B_t = 1.3 T (pellet) in all of helical devices have been achieved in the Large Helical Device (LHD). The b_t dependence of MHD activities has been investigated in NBI plasmas. The n/m = 1/2 mode excited in the core region and i = 1 resonant modes in peripheral region have been observed. Both of the fluctuation amplitudes increase with b_t and the pressure gradient. The strong n/m = 1/2 mode which affects plasma profile have been observed in high-b_t discharges and the abrupt disappearance of the mode leads to the restoration of T_e profile. Violent instabilities which terminate the plasma and degradation of global energy confinement have not been observed so far.

1. Introduction

In helical plasmas with no net currents, an understanding of pressure driven modes such as resistive/ideal interchange modes and ballooning modes have been a major key issue for realization of high-b plasmas. In a heliotron configuration, resistive/ideal interchange modes are expected to be unstable easily because there are magnetic hill even in high-b plasmas although magnetic well is formed from center region by the Shafranov shift. The characteristics of excited instabilities and critical beta value strongly depend on the feature of magnetic configuration. Heliotron-E has the strong magnetic shear for stabilization of ideal interchange modes, while there is strong magnetic hill in peripheral region. The internal disruption with particle and energy loss have been triggered by n/m = 1/1 mode in high–b plasmas with the large pressure gradient [1]. The control of the pressure profile with a strong gas puff has flattened the pressure gradient around the i = 1 surface, and the volume averaged beta value of 2 % was realized by the suppression of the internal disruption [2]. In Compact Helical System (CHS) with large finite beta effects related to low-aspect-ratio [3], the volume averaged equilibrium beta value of 2.1 % was achieved by confinement improvement given by means of turning off gas puff [4]. Then strong global instability was not observed [5].

Since LHD experiments were started in 1998, plasma parameters have been improved with the progress of heating power systems during every experimental campaign [6]. Recent experiments based on high power neutral beam heating enable us to obtain a volume-averaged beta value b_t of over 2 %, where b_t is defined as $2m_0<p>/B_{av}^2$ and B_{av} is averaged toroidal magnetic field in plasma region. The highest volume averaged beta value b_t of 2.2% at B_t = 0.75 T (gas puff) and 2.4 % at B_t = 1.3 T (pellet) in all of helical devices has been achieved in the *unstable* configuration with magnetic hill. In previous experiments, the pedestal structure has been observed and has made a great contribution to global plasma confinement [7,8]. However, the structure has formed large pressure gradient in peripheral region with magnetic hill. The $\boldsymbol{i}$ = 1 resonant modes has been observed in high-field (low-$\boldsymbol{b}$) plasmas and the relationship between pressure gradient and mode activity has been investigated [9]. On the other hand, n/m = 1/2 mode located in the core region also appears as threshold with b_t of about 0.3 % [10]. Here, observation results of MHD activity in NBI plasmas with higher b_t range with up to 2.2 % are reported.

2. High-b Experiments

Figure 1 shows the time behavior of high-b_t discharge of over 2 %. The magnetic axis position R_{ax} and toroidal magnetic field B_t are set at 3.6 m and 0.75 T, respectively. The target plasma was produced by a neutral beam of tangentially co-injection (NBI#2) and maintained by counter neutral beam injection (NBI#1) from 1.32 s addition to NBI#2. Hydrogen gas was supplied by gas puff from 0.6 s to the end of discharge, and line averaged electron density $\bar{n}_e$ gradually increase with time and approaches 3×10^{19} m^{-3}. The b_t^{dia} estimated by the diamagnetic flux measurement approaches about 2.2 % at 2.75 s. Net plasma current I_p flows in the co- direction and reaches about 20 kA at the end of discharge. It has been expected that this I_p is composed of Ohkawa currents produced by unbalanced NBI and bootstrap currents [11]. The b_t^{dia} is saturated at 2.45 s and increases again at 2.66 s. While $\bar{n}_e$ monotonically increase with time, the central electron temperature T_{e0} and the central plasma pressure decrease from 1.72 s and starts to rise at 2.68 s. The magnetic fluctuation with $f \leq 50$ kHz was measured in the time range from 1.7 s to 3.0 s, and the coherent modes with n/m = 1/2, 2/2 and 2/3 were observed. These modes have rotational frequency of 1kHz, 3 kHz and 8 kHz, respectively. The amplitude of n/m = 1/2 mode increases and saturate when b_t^{dia} = 2.1 %, and this mode abruptly disappears when b_t^{dia} starts to increase. The time at which the n/m = 2/3 mode starts to grow up is the same as the n/m = 1/2 mode

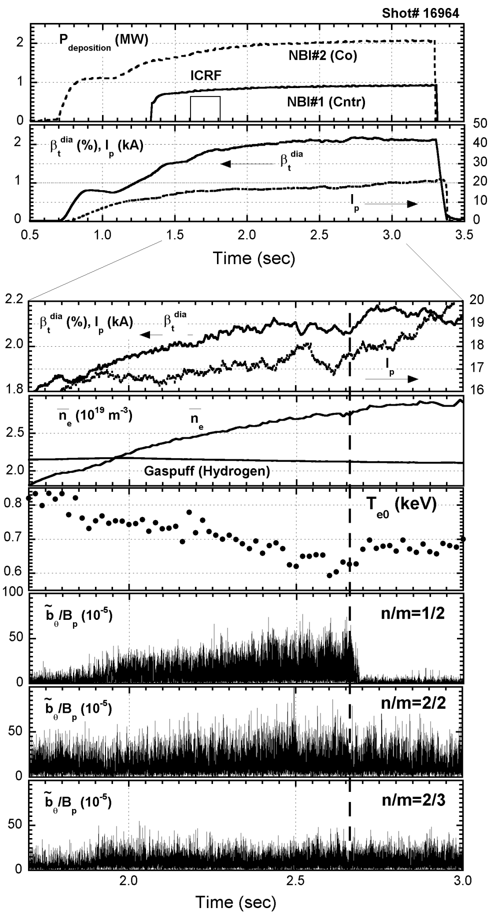

FIG. 1 Time behavior of high-b discharge with gas puff and the extended view in the time window from 1.7 s to 3.0 s.

case, and there is no change of the amplitude when the n/m = 1/2 mode disappears.

Figure 2 shows the rotational transform and T_e profiles before and after the disappearance of the n/m = 1/2 mode. The local flattening of T_e profile around ι = 1/2 surface has been observed when the n/m = 1/2 mode exists. Although this structure is intermittently observed, it appears conspicuously with the increase in the fluctuation amplitude of the n/m = 1/2 mode. The width of local flattening D/a is about 0.3, and this is consistent with an island width estimated by using measured radial component of the n/m = 1/2 mode amplitude. The T_e flattening disappears with the n/m = 1/2 mode after 2.66 s. Then T_e profile has recovered a peaked one and keeps the shape to the end of discharge. The $\bar{n}_e$ increases in this phase, with keeping the hollow profile.

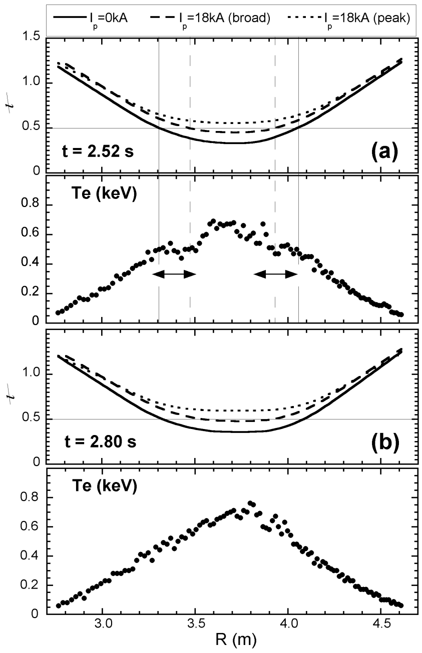

FIG. 2 Rotational transform and T_e profile at (a) 2.52 s and (b) 2.80 s.

One of the possibility of this phenomenon is the disappearance of the ι = 1/2 surface caused by plasma currents in the co- direction and finite-b effects. The similar phenomenon was also observed in Ohmic current experiments of CHS [12]. The rotational transform profiles shown in Fig.2 are calculated by using 3-D MHD equilibrium code VMEC [13] for the currentless case of I_p = 0 kA and the cases of I_p = 18 kA with broad current profile ($j = j_0\,(1- r^2)$) and peaked one ($j = j_0\,(1- r^2)^3$). Where $r = (Y)^{1/2}$ and Y is the toroidal flux function which is normalized by the value of the last closed flux surface. At 2.52 s, the T_e flattening is observed at R = 3.25 ~ 3.50 m and 3.85 ~ 4.10 m. The relation between these positions and predicted ι = 1/2 surfaces suggest that I_p has broader profile than that with $j = j_0\,(1- r^2)$. Also, the fact that I_p has a little change of 1 kA before and after an extinction of the n/m = 1/2 mode means that the disappearance of the ι = 1/2 surface may be caused by the change in the current profile rather than absolute value of I_p. The R_{ax} derived from T_e profile at 2.52 s is about 3.65 m and the Shafranov shift is relatively small because the decrease in central b value. After disappearance of the n/m = 1/2 mode, R_{ax} shifts to about 3.75m (at 2.8 s), which causes a rise of central rotational transform through Shafranov shift addition to the increase in I_p.

3. Beta Dependence of MHD modes

Figure 3(a) shows the changes in fluctuation amplitudes of observed global modes with $m \le 3$ with b_t^{dia} in 16 NBI plasmas with R_{ax} = 3.6 m and B_t = 1.5 T. Here, discharges with I_p of less than 5kA (at B_t = 0.75T) are selected except that with b_t^{dia} > 1.8 % in the case of Fig.1. This means that the changes in location of resonant surface due to I_p is relative small when $b_t^{dia} \le$ 1.8 % in this figure. The fluctuation amplitude is a root mean square of the mode amplitude in the time window of 20 ms and normalized by the vacuum magnetic field at probe position. Fluctuation amplitudes of ι = 1 resonant modes with n/m = 1/1, 2/2 and 3/3 increase with b_t^{dia} and reach about 10^{-4} when b_t^{dia} approaches about 2 %. The n/m = 1/2 mode appears when b_t^{dia} exceeds about 0.3 %. The fluctuation amplitudes keep to increase with b_t^{dia} and approaches 8×10^{-4} when b_t^{dia} is about 1.4 %.

The changes in the b gradients at the specific surfaces with b_t^{dia} are shown in Fig.3 (b).

The open circle and square are *b* gradients at *r* = 0.5 and 0.9, respectively, and they approximately correspond to the major rational *i* = 1/2 and 1 surfaces. The data are selected at the conditions that the plasmas reach quasi-steady state and gas puff is still turned on. The increase of *b* gradients at *r* = 0.5 in b_t^{dia} ≥ 0.5 % is larger than in b_t^{dia} < 0.5 % and this corresponds to the appearance of *n*/*m* = 1/2 mode. The *b* gradient at *r* = 0.9 increases linearly with b_t^{dia}.

The time development of *b* gradients at *r* = 0.5 and 0.9 surfaces in the discharge of Fig.1 (Shot#16964) are shown in Fig.3 (b). The time range is from 1.2 s to 3.3 s and divided into three phases, that is, A: before and B: during the growth of *n*/*m* = 1/2 mode, and C: after the disappearance of this mode. The *b* gradient at *r* = 0.9 increases and saturates during the phase A and keeps the constant to the end of discharge. This saturation depends on NBI power, and the same behavior of *b* gradient has been also observed in low-power discharges. In phase A (open triangle), the *b* gradient at *r* = 0.5 is much smaller than that in quasi-steady state plasmas and the amplitude of *n*/*m* = 1/2 mode is relatively small. In the phase B (closed triangle), while the *b* gradient abruptly rise to that in quasi-steady state plasmas with b_t^{dia} = 1.4 %, the *n*/*m* = 1/2 mode amplitude starts to increase. The amplitude approaches 7×10^{-5} at the end of phase B, and it is the same or small compared with the maximum value of *n*/*m* = 1/2 mode amplitude in b_t^{dia} ≥ 1.4 %. This fact suggests the possibility that *n*/*m* = 1/2 mode observed in b_t^{dia} ≥ 1.4 % also affect the plasma profile and restricts local *b* gradient. The restoration of pressure profile after the disappearance of the *n*/*m* = 1/2 mode in phase C is consistent with this suggestion.

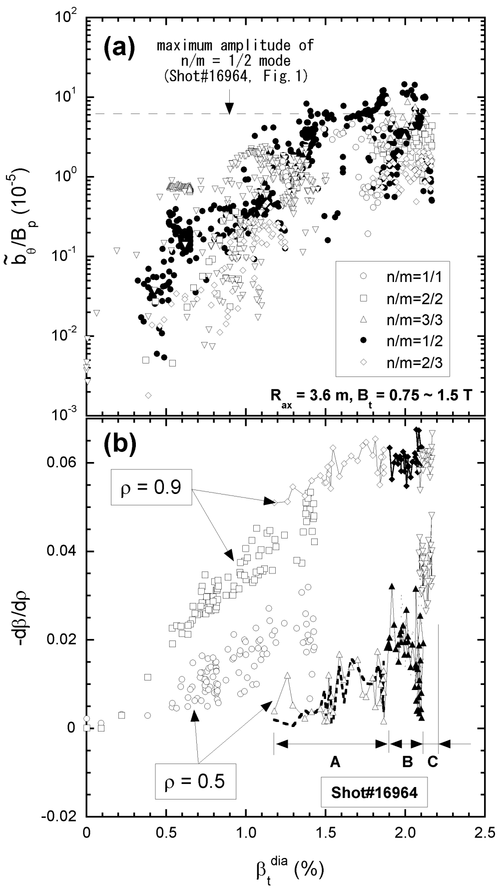

FIG. 3 (a) Changes in the amplitudes of observed coherent modes and (b) db/dr at r = 0.5 and 0.9 surfaces as a function of b_t^{dia}.

4. Discussions and Summary

In high-b_t experiments, a magnetic configuration with an inward-shifted R_{ax} of 3.6 m has been selected because neoclassical transport and particle confinement of high-energy ions are superior to the outward-shifted case. However, this configuration is unfavorable from the viewpoint of MHD stability. Theoretical prediction suggests that the high-*n* ballooning mode is unstable when the central beta is 8 % (peaked profile) [14], and destabilization of the interchange mode becomes a major concern. The stability beta limits estimated by the low-*n* ideal mode analysis and the Mercier criterion are higher for the outward shifted plasma than the inward shifted case because of magnetic well formation. The good energy confinement in the inward-shifted configuration has been obtained in experiments [15].

As experimental results, *i* = 1 resonant modes in peripheral region and the *n*/*m* = 1/2 mode in core region have been dominantly observed in the b_t^{dia} range of up to 2.2 %. The *i* = 1 resonant modes have been observed even in low-b_t region and the amplitude keep to increase with b_t^{dia} and pressure gradient. The *n*/*m* = 1/2 mode appears when b_t^{dia} reaches to

0.3% and the amplitude increases with b_t^{dia}. In the discharge with over 2 %, the n/m = 1/2 mode which affects the local b gradient has been observed. The reason for the growth of n/m = 1/2 mode amplitude in a discharge is the abrupt increase in local b gradient, which reaches about the same value as that in quasi-steady state plasmas with b_t^{dia} = 1.4 %. The maximum value of the n/m = 1/2 modes observed in $b_t^{dia} \geq 1.4$ % have the same or higher amplitudes compared with the n/m = 1/2 mode which affects plasma profile. There is a possibility that the local b gradient is limited by the n/m = 1/2 mode in b_t^{dia} ≥1.4 %. The restoration of the pressure profile due to the disappearance of n/m = 1/2 mode is consistent with the possibility.

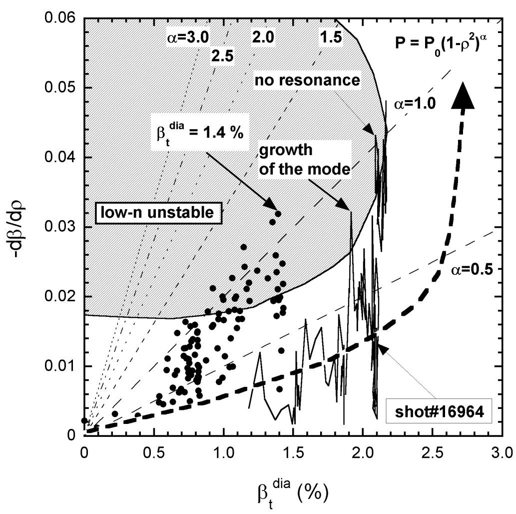

FIG. 4 Unstable region of ideal n/m = 1/2 modes in the plane of b_t^{dia} and b gradient at r = 0.5.

Figure 4 shows the unstable region of ideal n/m = 1/2 modes in the plane of b_t^{dia} and b gradient at r = 0.5. MHD stability has been calculated by the 3-D MHD stability analysis code TERPSICHORE [16] for different pressure profile. The measured b gradient at r = 0.5, which approximately correspond to i = 1/2 surface, fits that in the $P = P_0(1- r^2)^{0.5\sim1}$ cases. In this case, the present operational region is located in marginal against the low-n ideal instability. If observed n/m = 1/2 mode is related to ideal interchange mode, the discharge with keeping low b gradient in the unstable-b_t^{dia} region may realize the production of stable higher-b_t plasmas without destabilization of this mode (dotted line with an arrow in Fig. 4).

The authors would like to thank all members of the device engineering group for their operational support.

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