Stability in High-Beta Plasmas of LHD

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Abstract. In Large Helical Device (LHD), the volome averaged beta value $<\beta_{dia}>$ of 4.5 %, which is the highest value in all of heliotron/stellarators, was achieved by optimizing the magnetic configration from a virepoint of MHD characterisitcs, transport and heating efficiency of neutral beam. In this study, characteristics of MHD activities in extended $<\beta_{dia}>$ range over 4 % and the configuration dependence have been investigated. The dominant MHD modes moved from inner region to outer one when $<\beta_{dia}>$ increases, and the mode excited in the outermost resonance near plasma edge are enhanced in the $<\beta_{dia}>$ range over 4 %. The dependence of saturated amplitude of the mode on magnetic Reynolds number is close to that of linear growth rate of resistive interhcnage mode. When the magnetic shear was decreased and the plasma is close to m/n = 1/1 ideal stability boundary, the m/n = 1/1 mode suddenly growed and led to a minor collapse in the core region. The results suggest the significance of magnetic shear and a validity of a linear thory on ideal interchange mode. The mode can be stabilized easily by using external resonant field.

1. Introduction

High beta plasma production is a common subject in magnetic confinement systems for a realization of an efficient fusion reactor, and an understanding of MHD characteristics concerning beta-limit is the most important issue. Net-current free heliotron plasmas are free from current-driven instabilities unlike in tokamaks, and characterization of pressure-driven instabilities and control of them in the high beta regime are one of crucial issues towards for a helical fusion reactor. Since the heliotron has the configuration with weak magnetic shear in core region and magnetic hill in periphery, it is predicted that activities of ideal or resistive interchange instabilities are major key issues for high-beta plasma production. Especially, the understanding of peripheral modes excited by a steep pressure gradient in magnetic hill region is the common subject in helical device and tokamaks.

In Large Helical Device (LHD), the production of high beta plasma has progressed successfully with increasing heating power of neutral beam. The clear limitation of the beta value due to disruptive phenomena has not been observed in the standard operation, whereas several notable phenomena caused by MHD instabilities have been observed. In the medium $<\beta_{dia}>$ range of less than 3 %, the variation of plasma profiles with resonant magnetic fluctuations [1] and the minor collapse caused by formation of steep pressure gradient in the vicinity of the resonant surface after pellet injection [2] have been observed in the core plasmas, where $<\beta_{dia}>$ is the volume averaged beta value estimated by diamagnetic flux measurements. It is found that these phenomena occur in marginal region against ideal interchange mode [3]. These MHD activities have not been observed when $<\beta_{dia}>$ is increased, which suggests that the resonant surface enters the magnetic well region due to finite-beta effects.

On the other hand, MHD modes excited in the periphery with magnetic hill are enhanced with increasing beta and or L/H transition [4-6]. The relationship between peripheral pressure gradient and stability boundary against ideal low-n mode has been investigated in the $<\beta_{dia}>$ range with up to 4 % [7]. Also, in the $<\beta_{dia}>$ range with more than 3 %, peripheral MHD activities become stable spontaneously from the inner region to the outer region when $<\beta_{dia}>$ exceeds a certain value [8]. This interesting phenomena have been well observed especially in the $<\beta_{dia}>$ range of > 4 % [9].

In recent experiments, a control of a pitch parameter of helical coils, γ_c, was mainly performed in order to optimize the magnetic configuration for high-beta plasma production and investigate MHD characteristics. The γ_c is defined as $\gamma_c = 5a_c/R_0$ in the LHD case, where a_c and R_0 are minor and major radii of the helical coil, respectively. Since the helical coil is composed of three layers, the a_c can be widely changed by controlling each layer's current of helical coil. A decrease in γ_c causes an increase in central rotational transform, which reduces the Shafranov shift. A small γ_c is favorable for a heating efficiency and a transport because the outward shift of the magnetic axis leads to an increase in a helical ripple loss of particles. It is also suitable for raising an equilibrium beta-limit. However, a reduction of the plasma shift restricts spontaneous formation of magnetic well, and an increment of γ_c reduces magnetic shear [10]. The initial experimental results were already reported in Ref.9, and qualitative characteristics described above were verified. The optimum γ_c configuration was found out and then maximum beta of 4.3 % was obtained in FY2004 experiments [9].

In this paper, activities of MHD modes extended to higher beta range are described. Also, effects of configuration parameters such as the magnetic shear and magnetic hill/well, on MHD activities are considered through the γ_c-scan experiments.

2. History of High-β Experiments

Figure 1 shows changes of the minor radius, a_{eff}, the central rotational transform, $\iota_0/2\pi$, plasma aspect ratio, A_p, and achieved $<\beta_{dia}>$ as a function of γ_c. These are under the vacuum configuration with the magnetic axis, R_{ax}, of 3.6 m. Usually, the γ_c can be changed from 1.13 to 1.254, and the γ_c = 1.254 case is standard in LHD. The a_{eff} is decreased from 0.65 to 0.44 when γ_c is changed from 1.254 to 1.13, and then A_p is increased from 5.8 to 8.3. While the $\iota_0/2\pi$ is increased from 0.38 to 0.74, the edge $\iota/2\pi$ is almost constant to 1.6. The increments of $\iota_0/2\pi$ and A_p lead to decrease Shafranov shift.

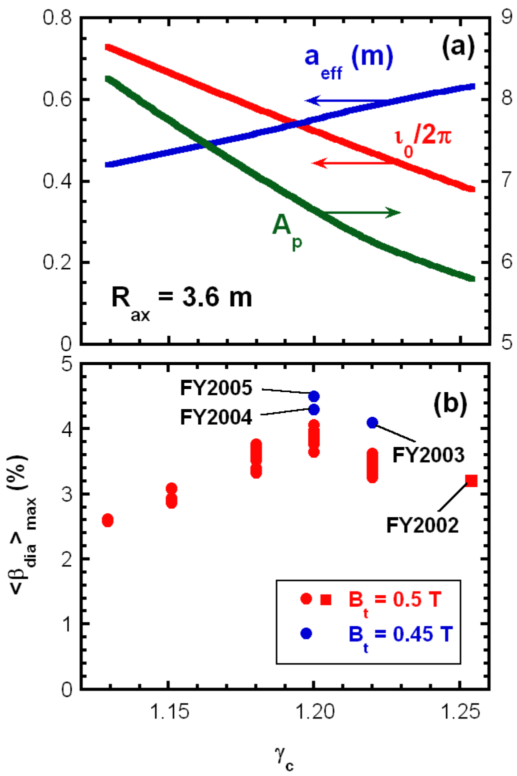

FIG.1 Changes of (a) a_{eff}, $\iota_0/2\pi$, A_p and (b) achieved $<\beta_{dia}>$ as a function of γ_c.

Achieved $<\beta_{dia}>$ in the configurations with different γ_c and toroidal magnetic field at R_{ax}, B_t, is shown in fig.1(b). The plasmas were heated by three neutral beam injections in all cases. The achieved $<\beta_{dia}>$ of 3.2 % was obtained in the configuration with γ_c = 1.254 (standard) in FY2002 experiments (red square) [11]. In FY2003, a small reduction of γ_c allows higher-beta plasma production and $<\beta_{dia}>$ of 4.1 % was achieved [7,8]. The γ_c dependence of achieved $<\beta_{dia}>$ was investigated in the configuration with B_t = 0.5 T (red circle) in FY2004 [9]. Then the total heating power was 10.5 MW. Achieved $<\beta_{dia}>$ increased with decreasing γ_c, whereas it gradually decreased when γ_c exceeded 1.20. Thus, the optimum γ_c of 1.20 was found out and then $<\beta_{dia}>$ of 4.3 %

was obtained. In the newest experiments, $<\beta_{\rm dia}>$ of 4.5 % was obtained at $B_{\rm t}$ = 0.45 and 0.425 T and $\gamma_{\rm c}$ = 1.20 [12]. Then the total heating power was 12 MW.

It is predicted that the increment of achieved $<\beta_{\rm dia}>$ with the reduction of $\gamma_{\rm c}$ is due to restraint of degradation of heating efficiency. According to Monte-Carlo calculation, the heating efficiency gradually increases from 0.85 to 0.95 when $\gamma_{\rm c}$ changes from 1.22 to 1.18, which is due to reduction of Shafranov shift. However, improvement factor of energy confinement, $H = \tau_{\rm E}/\tau_{\rm ISS95}$, gradually decreases from 1.5 to 0.7 when $\gamma_{\rm c}$ is decreased from 1.22 to 1.13 under the condition with line averaged electron density $\bar{n}_{\rm e} \sim 3\times10^{19}$ m^{-3} and $B_{\rm t}$ = 0.5-1.5 T, where $\tau_{\rm E}$ and $\tau_{\rm ISS95}$ are energy confinement times obtained from experiments and empirical scaling [9], respectively.

In the next section, MHD activities in the highest beta plasma of FY2005 experiments and the parameter dependence of MHD mode in the extended range of $<\beta_{\rm dia}>$ are described. Secondary, The reason for the reduction of $<\beta_{\rm dia}>$ and H-factor with decreasing $\gamma_{\rm c}$ is considered from a viewpoint of effects of edge MHD activities. The interesting MHD activities observed in low-magnetic shear configurations are introduced finally.

3. MHD characteristics in high-beta plasma

3.1. Highest-β discharge

Figure 2 shows the highest- β discharge with $<\beta_{\rm dia}>$ = 4.5 % in the $\gamma_{\rm c}$ = 1.20 configuration. The $R_{\rm ax}$ and $B_{\rm t}$ were set at 3.6 m and 0.425 T, respectively. The target plasma was produced and maintained by injecting two co- neutral beams and a counter one. The electron density was sustained by H_2 gas puff. The $<\beta_{\rm dia}>$ increased with $\bar{n}_{\rm e}$ and approached 4.5 % at 0.89 s. The gas puff was turned off at 1.35 s, whereas the plasma with $<\beta_{\rm dia}>$ > 4 % was maintained for $10\tau_{\rm E}$ or more till two neutral beams were turned off at 1.8 s.

The $R_{\rm ax}$ was identified by an electron temperature profile measured with Thomson scattering system. The Shafranov shift, $\Delta/a_{\rm eff}$, is less than 0.25 in the discharge, where Δ is defined as $\Delta = R_{\rm ax} - R_{00}$ and R_{00} is a central position of the last closed flux surface. The temporal change of $\Delta/a_{\rm eff}$ is almost consistent with that of $<\beta_{\rm dia}>$, except for the low-density regime (< 2 $\times10^{19}$ m^{-3}) where the beam pressure is relatively high. Thus, Shafranov shift is much smaller than equilibrium beta-limit defined as $\Delta/a_{\rm eff}$ = 1/2.

Peripheral MHD activities such as m/n = 1/1, 2/3, 1/2 and 2/5 were dominantly observed in fig.2 discharge, and they rotated with f < 15 kHz in the electron diamagnetic direction. The m/n < 1 modes appeared at the beginning of discharge, and the increment of $<\beta_{\rm dia}>$ was restrained by the abrupt growth of, especially, the m/n = 2/3 and 1/2 modes. However, when $<\beta_{\rm dia}>$ exceeds around 4 %, amplitudes of these modes gradually decreased and intermittently behaved or disappeared. Although the amplitude of m/n = 2/5 mode increases, it is relatively small compared with other modes. The tendency that MHD modes are suppressed from inner region

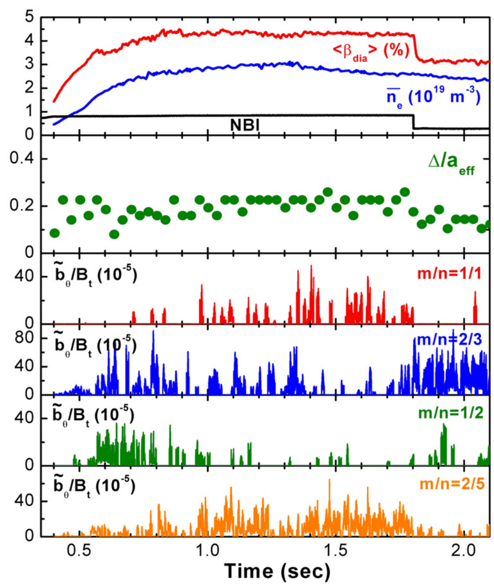

FIG.2 Typical MHD activities in high-β discharges in γ_c = 1.20 configuration.

to outer one has been well observed in the high-beta regime, and then profile flattening in the vicinity of the resonances occurred [8]. The observed peripheral MHD modes are not crucial for the production of high-beta plasma in the $<\beta_{dia}>$ range of > 4 %.

According to linear MHD analysis assuming an existence of the nested flux surface, the Mercier criterion D_I on $\iota/2\pi \geq 1$ surface, which is the index of ideal stability boundary, was less than 0.2 even in highest β plasma. Since theoretical prediction suggests that a criterion of low-n stability boundary corresponds to $D_I = 0.2$, the plasmas is expected to be marginally stable against ideal modes.

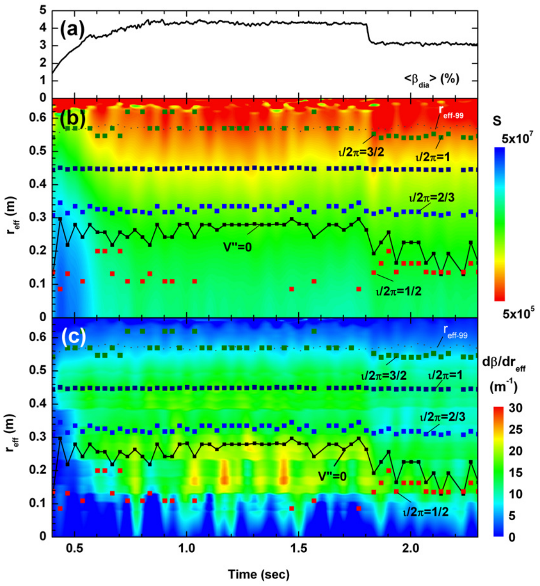

FIG.3 Temporal changes of (a) $<\beta_{dia}>$*, (b) S, and (c)* $d\beta/dr_{eff}$ *in the entire plasma, and the comparison with radial positions of plasma boundary, several resonant surfaces and* $V''=0$*.*

Figure 3 shows the temporal changes of $<\beta_{dia}>$ and radial profiles of magnetic Reynolds number, S, and β-gradient, $d\beta/dr_{eff}$, in the fig.2 discharge. The S and $d\beta/dr_{eff}$ were estimated by using electron density and temperature profiles which were measured with FIR interferometer and Thomson scattering system, respectively. Also, time evolutions of specific radial positions are shown in the figure.

Since an estimation of the accurate plasma boundary is difficult because of lack of measurement in the periphery, the location where the plasma has 99 % of the stored energy was used as an effective plasma boundary. It almost unchanged till the end of the discharge. The radius position with $V'' = 0$, which corresponds to the boundary of magnetic well/hill, depends on the Shafranov shift (Fig.2). The regime outside the $V'' = 0$ boundary corresponds to the magnetic hill. The resonant surfaces of observed MHD modes are on the magnetic hill, whereas the mode excited in the magnetic well region, for example, $m/n = 2/1$ mode, was not observed. In the magnetic well region, high β gradient is sometimes realized at t = 1.0-1.5 s. An intermittent disappearance of the $\iota/2\pi = 1/2$ surface is caused by an increment of central $\iota/2\pi$ due to finite-β effects. The $\iota/2\pi = 3/2$ surface is located in vicinity of $r_{eff\text{-}99}$, and the $\iota/2\pi > 3/2$ resonances are outside $r_{eff\text{-}99}$.

When the $m/n \leq 2/3$ modes were enhanced at 0.55 s, the S around $\iota/2\pi \geq 2/3$ surfaces abruptly increased despite the β gradients are almost constant (fig.3(b)). Also the increment of S on $\iota/2\pi = 2/3$ surface at > 1.8 s seems to enhance the $m/n = 2/3$ mode again. Since the increase in S on the $\iota/2\pi = 1$ surface is relatively small, the effect on the activity of the $m/n = 1/1$ mode is unclear in this discharge. The S dependence of the $m/n = 1/1$ mode is discussed in the next subsection.

The $m/n = 3/2$ mode has not been observed in high-β plasmas despite there is finite β gradient in magnetic hill configuration. It was found out in the previous experiments that the onset of the resistive mode strongly depends on S and D_R [13], where D_R is the index of the resistive stability boundary. The experimental results are consistent within a factor of 2 with a rough estimation of the stability boundary of a resistive low-n mode. The comparison with theoretical prediction is expected to make it clear.

3.2. Parameter dependence of MHD mode

In order to investigate the effect of the plasma parameters, especially, S, on MHD activity in the magnetic hill region, characteristics of the m/n = 1/1 mode in the wide S and I_p/B_t range has been summarized as an example. Figure 5 shows the amplitudes of m/n = 1/1 mode in the I_p/B_t - $<\beta_{dia}>$ and S - $<\beta_{dia}>$ diagrams, where I_p/B_t is a plasma current normalized by B_t. Data were obtained in the configurations with R_{ax} = 3.6 m, γ_c = 1.20 and B_t = 0.45-1T. The positive I_p/B_t decreases the magnetic shear. The I_p mainly consists of beam-driven and bootstrap currents. Since plasmas were almost heated by co-dominant neutral beams and it is theoretically predicted that bootstrap current flows in the positive direction, plasmas with positive I_p were dominant as shown in fig.4 (b).

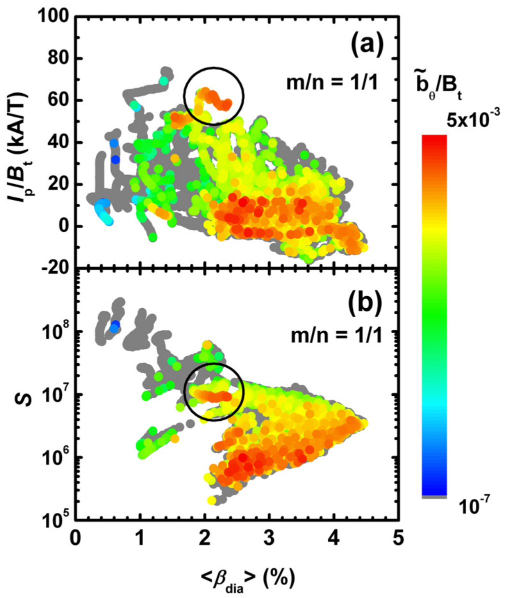

FIG.4 Amplitudes of m/n = 1/1 mode in the (a) I_p/B_t - $<\beta_{dia}>$ and (b) S - $<\beta_{dia}>$ diagrams.

The I_p/B_t dependence of the amplitude of the mode is unclear except for the specific area (surrounded by circle) as shown in fig.4 (a). The phenomena that the mode is enhanced when I_p/B_t exceeds a certain value have been observed [14], and it can be interpreted that plasmas come close to stability boundary of ideal interchange mode [1]. The amplitude of the mode is reduced when S is increased, and the saturation level of the mode has clear dependence of S rather than I_p/B_t (fig.4 (b)). Since the S is proportional to $B_tT_e^{3/2}/n_e^{1/2}$, this tendency means that the amplitude of the mode is reduced in configuration with strong field and high-temperature, which is favorable in high-beta and high-temperature reactor. We can see this tendency through the comparison of S dependence between in LHD and Compact Helical System (CHS) [1]. The quantitative estimation of S dependence of the amplitude of the mode has been done, and it is consistent with that of linear growth rate of resistive interchange mode [9].

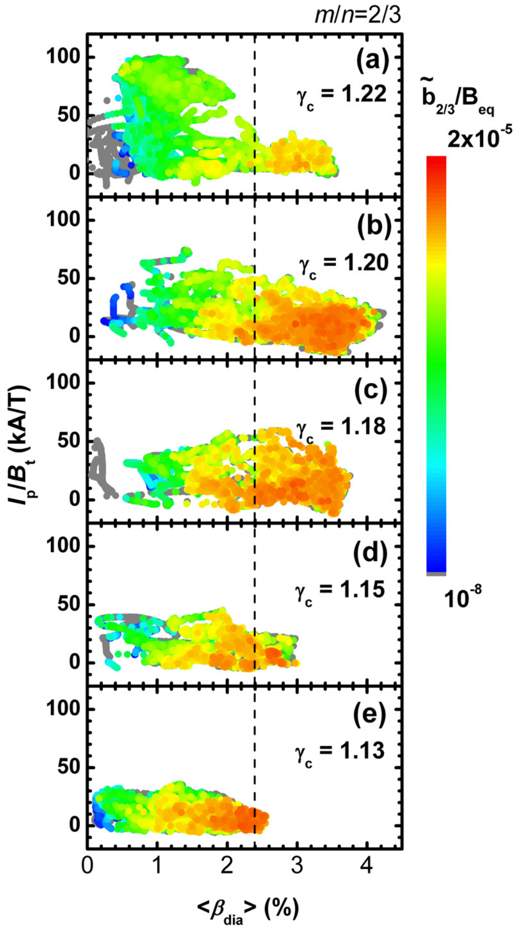

FIG.5 Amplitudes of m/n = 2/3 mode in the I_p/B_t - $<\beta_{dia}>$ diagrams in the configurations with different γ_c.

3.3. Behavior of Edge MHD mode

The $m/n \leq 1$ resonant modes have been dominantly observed in high-beta plasmas. In particular, m/n = 2/3 mode affects the plasma confinement, which is shown at the beginning of fig.2 discharge. It is also a key instability for H-mode plasma [4-6]. The resonant surface is located near the plasma edge in any γ_c configuration, whereas this mode has been dominantly observed in all configurations.

Figure 5 shows the amplitudes of the mode in the I_p/B_t and $<\beta_{dia}>$ diagram in different γ_c configuration. The data was obtained in γ_c -scan experiments in the configuration with R_{ax} = 3.6 m and B_t = 0.5-1T, as shown in fig.1(b). In order to compare the amplitude of the mode in different γ_c configuration, the normalized amplitude of the mode, $\tilde{b}_{2/3}/B_{eq}$, was applied here. The $\tilde{b}_{2/3}$ is the m/n = 2/3 amplitude on the plasma boundary, which is estimated by using the relation $\tilde{b}_m \propto 1/r^{-(m+1)}$, where r is the minor radius. The B_{eq} is an equilibrium poloidal field on the plasma boundary and defined as $B_{eq} = a_{eff}B_t\iota/(2\pi R_{00})$. The I_p dependence of the amplitude is relatively small. The $\tilde{b}_{2/3}/B_{eq}$ increases with the decrease in γ_c at the same $<\beta_{dia}>$. It is predicted that the activity of m/n = 2/3 mode leads to the degradation of the plasma confinement with reduction of γ_c.

Unfortunately, stability analysis and estimation of S dependence of this mode are difficult because of poor measurements in the edge and/or ergodic region, although the strong S dependence is seen in the fig.3 discharge. The resonant surface is moved to the outward direction by finite-β effects.

3.4. MHD activities in low-magnetic shear configuration

It has been found out that in the magnetic shear configurations, strong m/n = 1/1 mode abruptly appears and leads to the minor collapse in core plasma [9]. The reduction of the magnetic shear is caused by decreasing γ_c and/or increasing positive plasma current. The magnetic shear ,$d\iota/d\rho$, decreases from 2.8 to 1.1 in vacuum when γ_c decreases from 1.25 to 1.13. The V" also decreases from 0.8 to 0.1. When $<\beta_{dia}>$ increases, both $d\iota/d\rho$ and V" decrease. The changes of their parameters in the γ_c = 1.25 case are larger than the γ_c = 1.13 case because of the difference of Shafranov shift.

Figure 6 shows an example of the minor collapse observed in the configuration with γ_c = 1.13 and B_t = 1 T. After the $<\beta_{dia}>$ increased with $\bar{n}_e$, it abruptly reduced at 0.84 s. Then I_p/B_t is less than 20 kA/T, which is relatively small. The $\tilde{b}_{r11}/B_t$, which is radial component of m/n = 1/1 perturbation on the resonance and estimated by saddle loop measurements, started to increase just before the collapse. After that, the $\tilde{b}_{r11}/B_t$ synchronized the $<\beta_{dia}>$ signal, which means the mode affects the plasma confinement directly. Several experiments results show that this kind of m/n = 1/1 mode has no rotation and grows at the specific position [9]. The mode rotating with an order of electron diamagnetic frequency, which is well observed in the experiments, was not observed in this discharge. The S parameter is about 10^8, which is relatively high compared with highest-beta discharge ($S \sim 10^6$). This may be one of reasons for disappearance of the rotating mode as shown in fig.4.

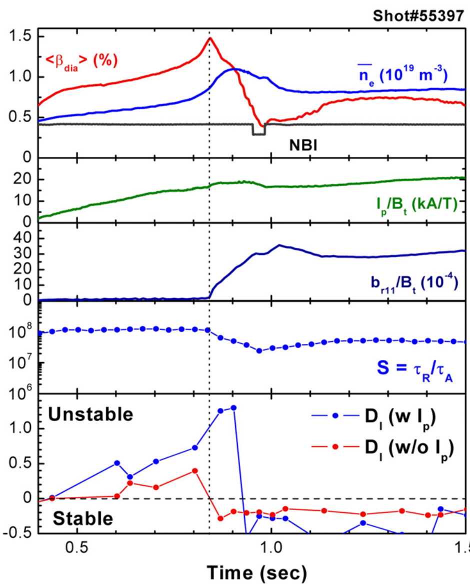

FIG.6 Minor collapse observed in γ_c = 1.13 configuration.

The bottom figure shows the temporal change of D_I on the $\iota/2\pi$ = 1 resonant surface, where D_I is Mercier criterion, which is well used as the index of ideal stability boundary and D_I < 0 means that ideal mode is stable. The current profile is assumed as $j(\rho) = j_0(1-\rho)^2$. The DI has the positive value from the beginning of the discharge even in the currentless case, and the D_I with the I_p effect approached 0.7 at 0.803 s just before the collapse. The increment of D_I is caused by reduction of magnetic shear due to I_p as well as the increase in the pressure gradient. Even in the currentless discharge, the growth of this mode has been observed.

The figure 7 shows the temporal changes of T_e profiles before and after the collapse. The flattening of T_e profile in vicinity of $\iota/2\pi = 1$ surface appeared with the growth of the mode. The mode extended the width of the flattening, and it led to the reductions of central T_e and plasma volume.

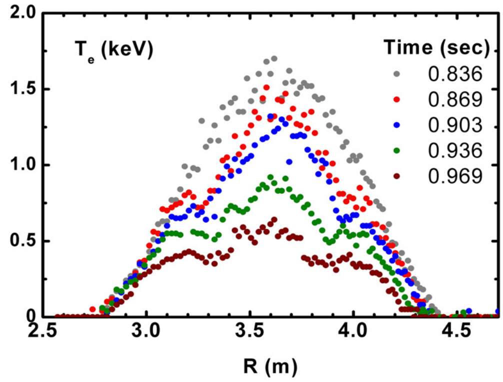

FIG.7 Temporal changes of Te profiles in fig.6 discharge.

The appearance of *non-rotating m/n* = 1/1 mode (NR mode) in the $<\beta_{dia}>$ and $\iota_0/2\pi$ diagram is shown in fig.8. The difference color corresponds to the amplitude of the radial component of the NR mode. Since edge iota is about 1.6 in any γ_c configurations, the central $\iota/2\pi$ is correlated with magnetic shear around $\iota/2\pi = 1$ resonance. The mode appears in high- $\iota/2\pi$ region and clear operational limit was found out. This limit is qualitatively consistent with the ideal stability limit. On the other hand, in a configuration with high-shear and low plasma current, plasmas can approach to the high-beta region passing through the "*stable*" area.

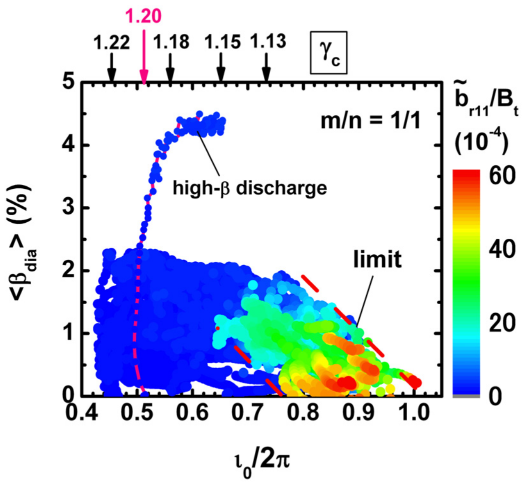

FIG.8 Appearance of non-rotating m/n = 1/1 mode in the $<\beta_{dia}>$ and $\iota_0/2\pi$ diagram.

4. Discussion and summary

High-β plasma of 4.5 % was successfully obtained through the γ_c-scan experiments and maintained for much longer time than the energy confinement time. There is no clear degradation of the maximum $<\beta_{dia}>$ with increasing power of neutral beams [13]. While peripheral MHD activities have been dominantly observed in high-β regime, no strong instability that terminates the plasma has appeared. The MHD modes are suppressed or intermittently behave in the high-beta regime of 4 %. The Shafranov shift is much smaller than that predicted as the equilibrium beta-limit. However, it still decreases the heating efficiency. The active control of the magnetic axis is expected in order to maintain the high heating efficiency.

The enhancement of MHD modes in the magnetic hill region with S has been observed in one discharge. The clear *S* dependence of the amplitudes of MHD modes has been found out, and it is almost the same as that of the linear growth rate of the resistive interchange mode. The relationship between the nonlinear saturation level and *S* is theoretically unclear yet. The experimental facts suggest that at least, low-*n* MHD activity in the magnetic hill becomes to be more stable in the high-S plasma, and it is favourable for fusion reactor with it. Also, it becomes the important knowledge for considering the technique of the mode stabilization.

The *H*-factor gradually degrades from 1.6 to 1.0-1.2 when $<\beta_{dia}>$ increases to 4 % [9]. No clear effect of low-*n* MHD activities on achieved $<\beta_{dia}>$ has been observed. The transport analysis indicates that the thermal transport in the periphery significantly degrades with an increment of $<\beta_{dia}>$, and the transport coefficient in high-beta regime is about ten times larger in a prediction by gyro-reduced Bohm model [16]. As one of the reasons for the degradation, a turbulence caused by resistive-g mode has been considered. The predicted transport coefficient in periphery is quantitatively consistent with experimental results. The turbulence is caused by the decreases of *S* and magnetic shear, and an enhancement of magnetic hill as well as pressure gradient. Thus, reduction of the transport due to the turbulence is expected in high-*S* plasma as well as the low-*n* mode.

On the other hand, it is predicted that the turbulence due to resistive-g mode is increased with decreasing γ_c. The experimental results show that the m/n = 2/3 mode excited near the edge is enhanced with the reduction of γ_c. In addition, strong m/n = 1/1 mode leads to the minor collapse in the core plasma, and it grows near the marginal region of the ideal stability boundary. Recent experiments indicate that the strong m/n = 1/1 mode is suppressed by giving the resonant magnetic field by external coils [17]. These results show the significance of, especially, the magnetic shear, and give the important information on the optimal magnetic configuration for helical fusion reactor.

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