Recent Progress of MHD Study in High-β Plasmas of LHD

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Abstract

This article describes a recent progress of MHD study in high-beta plasmas of Large Helical Device (LHD). The control of plasma aspect ratio (A_p) in the range with 6.3-8.3 were done to optimize the configuration for high-beta plasma production and to investigate MHD characteristics. The experiments brought a maximum average beta of 4.3 %. MHD activities in periphery are dominantly observed in such a high-beta region, and their amplitudes increase with decreasing magnetic Reynolds number (S). The S dependence of the mode amplitude is much stronger than theoretical prediction on linear growth rate of resistive interchange mode ($\gamma \propto \beta^{2/3}S^{-1/3}$). When the plasma aspect ratio is increased, minor collapse due to m/n = 1/1 mode without the rotation occurs. It is enhanced further by the plasma current reducing magnetic shear and degrades the beta value by more than 50 %. The results are expected to give the important information on the operation regime and the future design of helical fusion reactor and to contribute to experimental knowledge on ideal instability.

1. Introduction

High beta plasma production is the common subject in magnetic confinement systems for a realization of an efficient fusion reactor, and an understanding of magneto-hydrodynamics (MHD) characteristics concerning β-limit is the most important issue. Net-current free plasmas in stellarator-heliotrons are free from current-driven instabilities unlike in tokamaks, and characterization of pressure-driven instabilities and control of them in the high-β 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-β 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 [1].

Since Large Helical Device (LHD) experiments started from 1998, the production of high-β plasma has progressed successfully with increasing heating power of neutral beam and it enables an exploration of MHD study. While the clear limitation of the beta value due to their instabilities such as disruptive phenomena has not been found in the standard operation, several notable phenomena caused by MHD instabilities have been observed. The variation of plasma profiles with resonant magnetic fluctuations [2] and the minor collapse caused by formation of steep pressure gradient in the vicinity of the resonant surface after pellet injection [3] have been observed in the core plasmas. These phenomena have been well observed in marginal region against ideal interchange mode [4]. On the other hand, MHD modes excited in periphery with magnetic hill are enhanced with the increasing β and/or L/H transition [5]. The relationship between peripheral pressure gradient and stability boundary against ideal low-n mode has been investigated in the $<\beta>$ range with up to 4 % [6]. Also, in high-$<\beta>$ range with more than 3 %, peripheral MHD activities spontaneously become stable from the inner region to the outer region when $<\beta>$ exceeds a certain value [7].

This article describes recent progress in MHD study based on high-β experiments performed in FY2004. In the experiments, a control of a plasma-aspect-ratio, A_p, was mainly performed for producing higher-β plasma and investigating the configuration dependence of MHD characteristics. An increment of A_p brings out an increase in rotational transform and restricts Shafranov shift. It is favourable 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. Also, it is suitable for raising an equilibrium beta-limit. However, a reduction of the plasma shift restricts magnetic well formation, and an increment of A_p reduces magnetic shear and enhances magnetic hill [8]. Therefore, the purposes of the experiments are (1) to explore the optimal A_p to the contrary conditions described above for high-β plasma production and (2) to investigate the effects of "*unstable*" configurations on MHD activities under the condition with the good transport property.

Experimental conditions are described in the next section. Section 3 indicates the experimental results, and the Shafranov shift in different A_p configurations are written in section 3-1. As the first topics, MHD activities observed in high-β discharges and the dependence of magnetic Reynolds number on MHD modes are discussed in section 3-2. In section 3-3, A_p dependence of MHD activities and their effects on plasma confinement is discussed as second topics. Experimental results are summarized and discussed in final section 4.

2. Experimental Conditions

The LHD is the heliotron device with a pair of continuous helical coils and three pairs of poloidal coils and all of coils are superconductive. The magnetic axis position R_{ax} can be changed from 3.4 to 4.1 m by controlling poloidal coil currents, and it can change the characteristics of transport and MHD stability. In the configuration with the inward shift of R_{ax}, particle confinement is better than the outward shifted case because an effective helical ripple loss of neoclassical transport decreases. In contract, the inward shifted plasma has a disadvantage for MHD stability due to the magnetic hill formation. The R_{ax} of 3.6 m was applied in the high-β experiments because highest energy confinement has been obtained and serious MHD activities have not been observed in previous experiments [9].

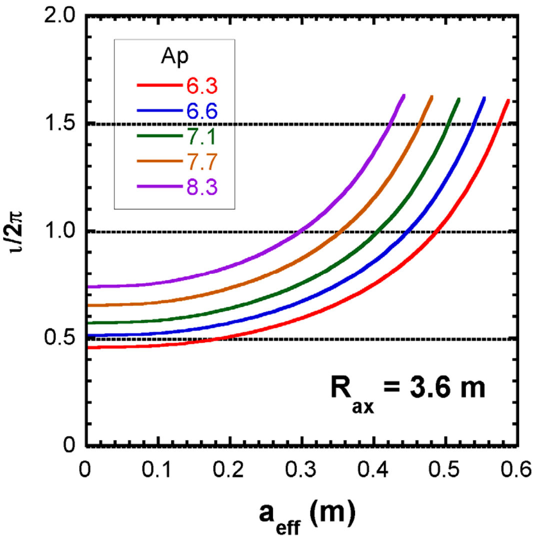

Fig.1 Rotational transform profiles against effective minor radius in different A_p

The LHD has another free degree of the magnetic configuration, namely, the plasma aspect ratio A_p. The helical coil is composed of three layers and the control of the central position of helical coil current which can widely changes A_p. In the experiments, A_p was changed from 6.3 to 8.3 in the R_{ax} = 3.6 m configuration. Figure 1 shows the rotational transform profiles against effective minor radius a_{eff} in different A_p, which are in the vacuum condition. Any rotational transform $\iota/2\pi$ increases in an entire region of a plasma. The central $\iota/2\pi$ increases from 0.45 to 0.75 when A_p changes from 6.3 to 8.3, which is expected to reduce Shafranov shift because the shift is analytically proportional to $1/A_p$ in low-β and large aspect ratio approximation. The reduced shift contributes to maintain good characteristics of the transport and heating efficiency, whereas it obstructs magnetic well formation in the plasma core and a large rotational transform makes magnetic hill higher [8].

As the experimental condition, toroidal magnetic field B_t was set at -0.45 ~ -1 T. The negative sign corresponds to direction of B_t, which is related with an injection direction of the neutral beams. Two co- and one counter Neutral Beam Injection (NBI) systems were applied as heating sources and the total port-through power is less than 12 MW. Electron density is controlled by Hydrogen gas-puff. Electron temperature and density profiles were measured with Thomson scattering and FIR interferometer, respectively. For identifying MHD modes, 22 magnetic probes and 24 saddle loops were used mainly.

3. Experimental Results

3-1 Shafranov shifts in different plasma-aspect-ratio

Figure 2 (a) shows the R_{ax} shift as a function of $<\beta_{dia}>$ in different A_p configurations, where $<\beta_{dia}>$ is defined defined as $4\mu_0/3\cdot W_{dia}/(B_{av0}2V_{p0})$. The W_{dia} is the diamagnetic energy, and B_{av0} and V_{p0} are averaged toroidal magnetic field inside the plasma boundary and plasma volume, respectively, and both of them are estimated under vacuum condition. The R_{ax} is estimated by electron temperature profile measured with Thomson scattering system. Data's at B_t = -0.5 and -1 T are applied here. The amount of the shift at A_p = 6.3 is 0.2 ± 0.08 m when $<\beta_{dia}>$ ~ 3 % and clearly reduces with increasing A_p. Shafranov shift Δ, which is defined as $(R_{ax} - R_{00})/a_{eff}$, against $<\beta_{dia}>$ is shown in Fig.2 (b), where R_{00} is the position of the geometrical center of the last closed flux surface. In the vacuum condition, Δ is about -0.12 in

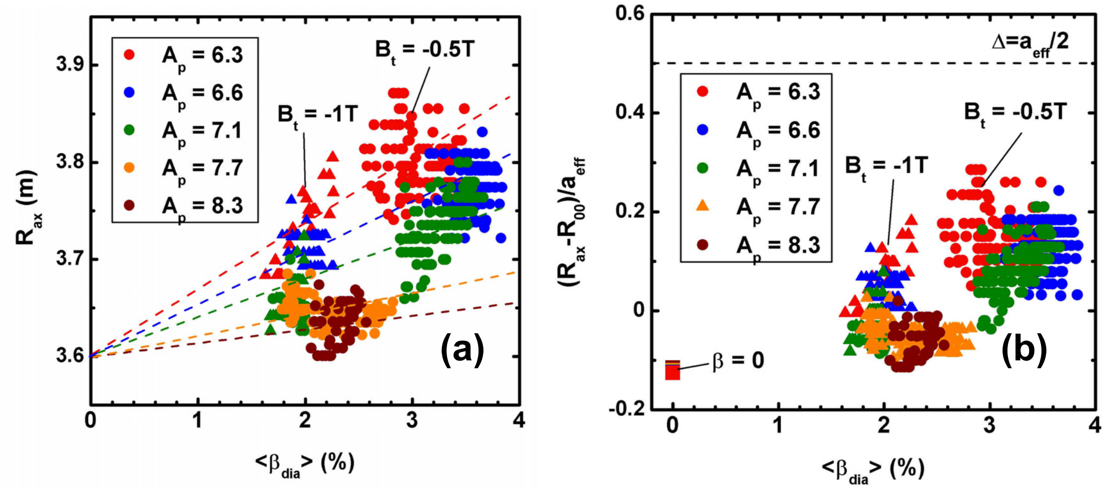

Fig.2 (a) R_{ax} shift and (b) Shafranov shift as a function of $<\beta_{dia}>$ in different A_p.

any A_p configuration, which means that R_{ax} is shifted to the inward compared with R_{00}. The maximum Δ at $A_p = 6.3$ is 0.3 when $<\beta_{dia}> \sim 3$ %, and it is much smaller than the equilibrium β-limit defined as $\Delta / a_{eff} = 1/2$ which is well used in low-β and large aspect ratio approximation. In the experiments, maximum $<\beta_{dia}>$ was obtained in the configuration with $A_p = 6.6$.. Therefore, the β-limit becomes higher than low- A_p case. According to a heat deposition power calculated by three dimensional Monte-Carlo simulation code [10], in plasmas with $<\beta_{dia}> = 3$ % and line averaged electro density $\bar{n}_e = 1.5 \sim 3 \times 10^{19}$ m^{-3}, the heating efficiencies at $A_p = 6.3$ and 7.1 are 0.85 and 0.9, respectively. Also the calculation results show that the heating efficiency decreases with the R_{ax} shift. Thus, the reduction of R_{ax} shift is effective to restrain the decrease in the heating efficiency.

3-2 MHD activities in high-beta regime

Figure 3 shows the highest-β discharge in the configuration with $A_p = 6.6$ and $B_t = -0.45$ T. Target plasma was produced and maintained by only three NBI's. The $<\beta_{dia}>$ increases with $\bar{n}_e$ and approaches 4.3 % at 1.18 s. MHD modes excited in periphery, i.e. $m/n = 1/1$, 2/3, 1/2 and 2/5 modes are dominantly observed in such high-β region. MHD activities till 1.18 s indicate that the $m/n = 1/1$, 2/3 and 1/2 do not grow so much despite $<\beta_{dia}>$ approaches the steady-state, whereas $m/n = 2/5$ mode excited in the outermost resonance is enhanced. This tendency is well observed in the $<\beta_{dia}>$ range of more than 3 %, and then peripheral modes are suppressed from inner region to outer one with increasing β [7]. In this discharge, $\bar{n}_e$ continues to increase to the end of discharge and the radiation collapse occurs the moment one NBI is turned off at 1.56. The $<\beta_{dia}>$ slightly decrease when $\bar{n}_e$ exceeds 2.5×10^{19} m^{-3}. Then peripheral modes, especially, $m/n = 1/2$ mode in this discharge, are enhanced again. The behaviour of MHD modes seems to vary according to electron temperature and density even at the same $<\beta_{dia}>$, and this can not be interpreted by only the increase and decrease in the pressure gradient.

Magnetic Reynolds number S is an important parameter concerning a topology of magnetic structures such reconnection phenomena. The S parameter is defined as $S = \tau_R / \tau_A$, where τ_R and τ_A are resistive time and poloidal Alfvén time, respectively. The linear growth rate of resistive interchange mode is well known as $\gamma \propto \beta^{2/3} S^{-1/3}$. As an example, several parameter dependences of the amplitude of the $m/n = 1/1$ mode in the configuration with $A_p = 6.6$ and $B_t = -0.4 \sim -1$ T are shown in Fig.4. As shown in Fig.4 (b), the envelope of mode amplitudes as a function of $<\beta_{dia}>$ indicates that it saturates and decreases when $<\beta_{dia}>$ increases. It is possible to interpret this tendency by considering the S dependence of the mode

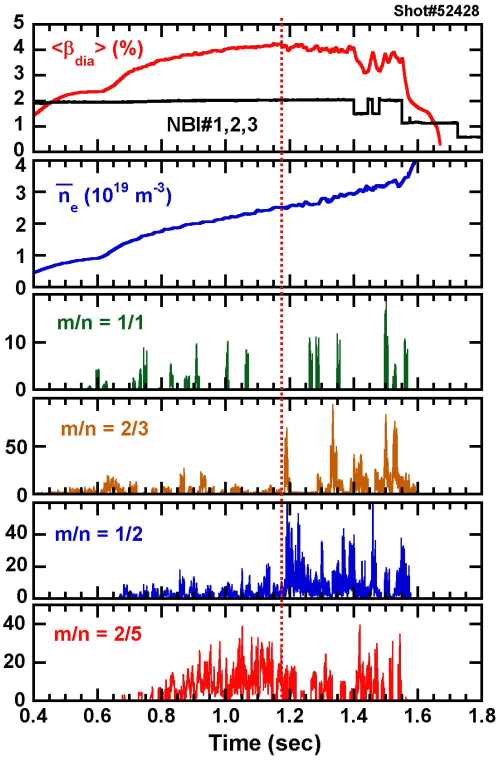

Fig.3 Typical MHD activities in high-β discharges in configuration with $A_p = 6.6$

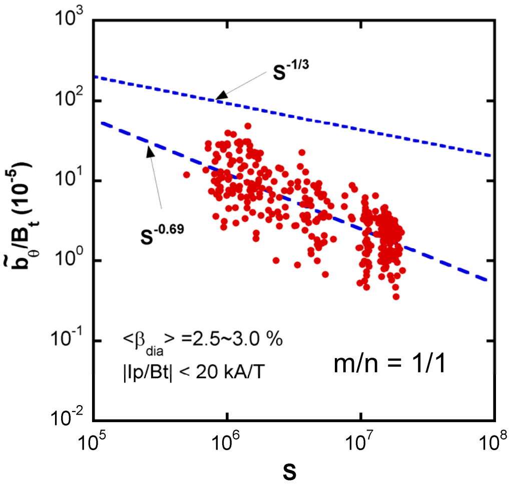

Fig.5 Change of the amplitude of m/n = 1/1 mode as a function of S parameter

amplitude (Fig.4(c)). The mode amplitude is enhanced clearly when S parameter decreases. The reduction of S parameter is caused by a decrease in B_t and an increase in $\bar{n}_e$, which corresponds to reduction of T_e under the condition of the same heating power. This means that MHD activity is expected to be suppressed in high temperature plasma. MHD mode also depends on the normalized plasma current I_p/B_t, and the mode is enhanced when I_p/B_t reducing magnetic shear largely increases (red circle shown in Fig.4 (a) and (c)).

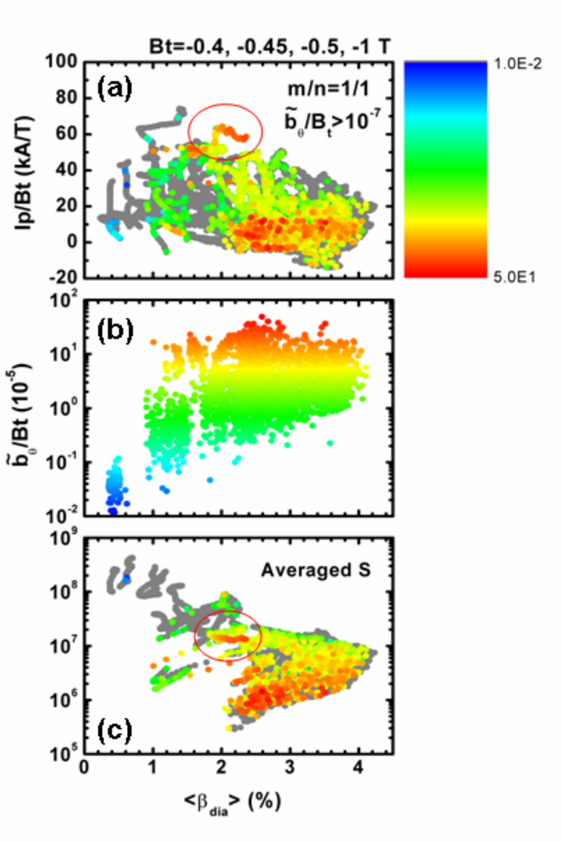

Fig. 4 Amplitude of m/n = 1/1 mode in (a) I_p/B_t and $\langle\beta_{dia}\rangle$, and (c) S and $\langle\beta_{dia}\rangle$ planes based on (b) $\langle\beta_{dia}\rangle$ dependence of coloured mode amplitude.

Figure 5 shows the change of the mode amplitude as a function of S parameter. The plotted data's are selected in plasmas with $\langle\beta_{dia}\rangle = 2.5 \sim 3$ % and $|I_p/B_t| < 20$ kA/T in order to remove other factors destabilizing the mode. The amplitude decreases with increasing S parameter, and the S dependence is much stronger than that predicted by a linear growth rate of a resistive interchange mode. According to a linear MHD theory, the mode intended in Fig.5 is stable to ideal instability and unstable to resistive one, which means that a comparison with the resistive model is valid in the framework of the linear stability. However, since the observed mode is predicted as the saturated state after nonlinear process, the validity of comparison with the linear growth rate and of an applicable range of S parameter should be considered. The S dependence of nonlinear saturation level is not clear so far.

3-3 Configuration dependence of MHD activities

As shown in Fig.1, the locations of resonances are changed by increasing A_p. In the A_p < 6.6 case, there are the $\iota/2\pi = 1/2$ resonant surface in the core, and the mode excited there sometime affects core pressure profile when β increases or the plasma current increasing $\iota/2\pi$ exists [2]. This mode completely disappears in high-β region. While there is no $\iota/2\pi = 1/2$

resonance at $A_p \geq 6.6$, $\iota/2\pi = 1$ resonance comes into the core with increasing A_p in spite of no stabilization effect due to magnetic well. Moreover, the plasma current decreasing magnetic shear destabilizes the mode further. Hence the $m/n = 1/1$ mode is expected to be the most noteworthy object from a viewpoint of MHD study and the future design of magnetic configuration.

Figure 6 shows the temporal changes of plasma parameters in the configuration with $A_p = 8.3$, $B_t = -1$ T and $|I_p/B_t| < 10$ kA/T. After $<\beta_{dia}>$ increases with $\bar{n}_e$, the minor collapse occurs at 0.58 s and an abrupt reduction of T_e was observed then. The $<\beta_{dia}>$ increases again with $\bar{n}_e$, whereas central T_e keeps maintaining almost the same T_e at $\rho = 0.5$ to the end of the discharge. Although Shafranov shift is observed just after the collapse, it disappears to the end despite $<\beta_{dia}>$ increases (Fig.6(c)). Figure 6(e) and (f) show the temporal changes of $m/n = 1/1$ component of the radial magnetic flux $\Delta\Phi_{1/1}$ normalized by B_t and the toroidal angle $\phi_{1/1}$ where the O-point of the structure is located at the outer torus. The $\Delta\Phi_{1/1}$ is estimated by using differential signals of two poloidal arrays of saddle loops which are away by 180 degrees in the toroidal direction. Generally, the poloidal profile of the differential signals is always zero even if there is a plasma with finite β because the poloidal profile of the magnetic field due to equilibrium currents has toroidal periodicity of $n = 10$ and they are cancelled out. Thus, the mode structure, the amplitude and toroidal angle is identified by the profile of the signals. If the magnetic shear is constant, the $\Delta\Phi_{1/1}/B_t$ is proportional to w^2, where w is the island width. In the Fig.6 discharge, $\Delta\Phi_{1/1}/B_t$ is nearly zero before minor collapse, and it suddenly increases with the occurrence of the minor collapse. After that, this mode saturates and maintains the amplitude to the end of the discharge. The toroidal angle is about 60 degrees when the mode grows, and it gradually increases to about 90 degrees. The precursor of the collapse is not clear and the analysis of the magnetic fluctuation indicates that $m/n = 2/3$ mode is dominant. Te profiles just and after the minor collapse

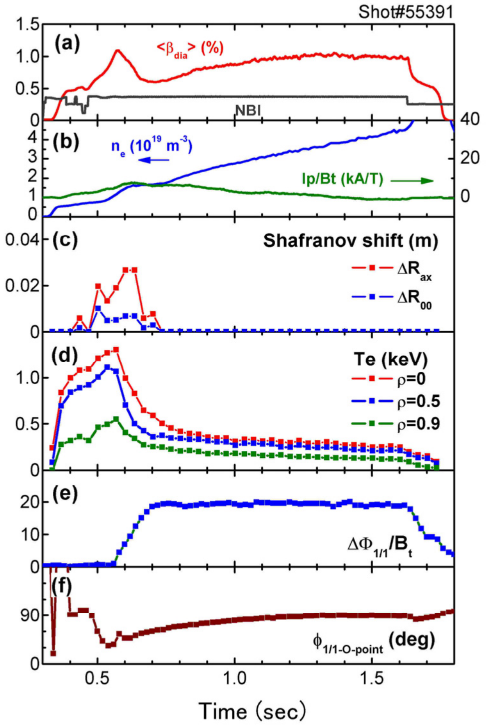

Fig.6 Minor collapse observed in the configuration with $A_p = 8.3$ and $|I_p/B_t| < 10$ kA/T

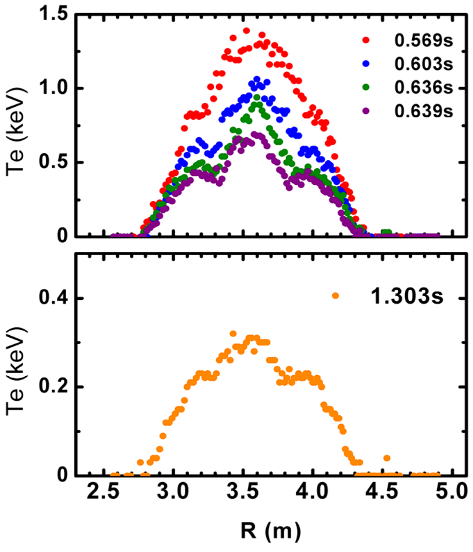

Fig.7 T_e profiles at 0.569, 0.603, 0.636, 0.639 and 1.303 s in the Fig.6 dischage.

in the Fig.6 discharge are shown in Fig.7. The flattening structure of Te profile appears around $\iota/2\pi = 1$ resonance at 0.569 s, and T_e in core region decreases with an extension of the flattening. This structure is maintained to the end of the discharge as shown in T_e profile at 1.303 s. The flattening structure at each time is almost consistent with the guess from the toroidal angle measured with flux loops.

The amplitude of this mode strongly depends on the plasma current. Figure 8 shows temporal change of the $m/n = 1/1$ mode the discharge with large positive I_p/B_t of less than 25 kA/T. The I_p is almost composed of only beam-driven currents and increased by keeping the constant $\bar{n}_e$ of 2×10^{19} m^{-3}. In this discharges, the mode grows at 0.58 s before $<\beta_{dia}>$ saturates, and it abruptly causes large collapse of β. The amplitude increases with the Ip/Bt and maximum value is 2.5 times as large as the Fig.6 case. It starts to decrease when I_p/B_t decreases by turning off one of NBI's. The $<\beta_{dia}>$ recovers with decreasing $\Delta\Phi_{1/1}/B_t$. The $\phi_{1/1}$ is about 60 degrees and the spatial location of the mode is almost constant in this discharge.

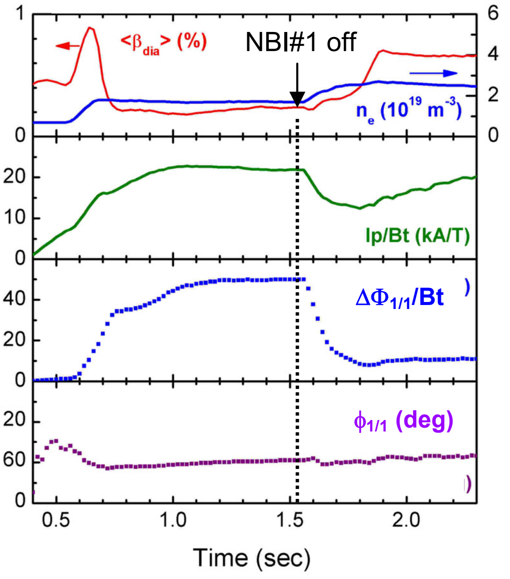

Fig.8 Temporal change of $m/n = 1/1$ mode in the discharge with maximum $|I_p/B_t| \sim 23$ kA/T in the configuration with $A_p = 8.3$ and $B_t = -1$ T

The excitation of such the "non-rotating" $m/n = 1/1$ mode leads to the serious degradation of β and confinement. The appearance of this mode in the configuration with each A_p is shown in Fig.9. The appearance strongly depends on the I_p/B_t in any A_p configuration and the threshold decreases with increasing A_p. This tendency suggests that one of reasons for the excitation of this mode is reduction of magnetic shear and enhanced magnetic well due to the increase in rotational transform. At $A_p = 8.3$, this mode occurs even in "currentless" configuration. Therefore, the excitation of this mode is deeply related with the formation of the rotational transform profile.

4 Discussion and Summary

High β plasma of 4.3 % was successfully

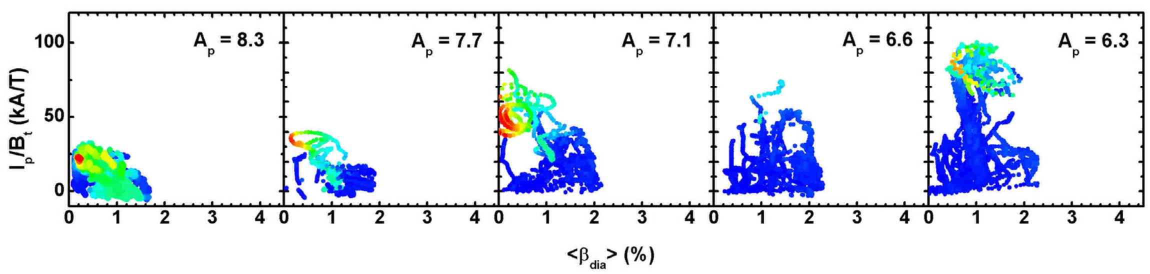

Fig.9 A_p, I_p/B_t and $<\beta_{dia}>$ dependences of the appearance of "non-rotating" $m/n = 1/1$ mode in the configurations with $B_t \leq -0.75$ T. The colour of data corresponds to the amplitude of the mode and the change from blue to red corresponds to 0 to 50 of the $\Delta\Phi_{1/1}/B_t$.

obtained through A_p control experiments. Although no large improvement of the plasma confinement has been observed, the reduction of Shafranov shift and the increment of heating efficiency contribute to increase achieved $<\beta_{dia}>$ slightly. Peripheral MHD activities are one of the key issues to produce higher-β plasmas in the future because of steep pressure gradient in the magnetic hill region and reduction of magnetic shear due to finite-β effects. In the present beta region, these activities do not give a clear limitation of β, the enhancement of peripheral MHD modes has not been observed. Destabilizations of these modes in high-density regime can be interpreted by decreasing magnetic Reynolds number. However, the dependence of the amplitude of the mode on magnetic Reynolds number seems to be much larger than predicted linear growth rate, and the reason is not clear so far. For the interpretation of the mode activity, several kinetic effects, validity of resistive model and so on should be considered.

The excitation of “non-rotating” $m/n = 1/1$ mode clearly limits the operational regime, and the impact to the profile and the confinement is much stronger than the case of $m/n = 2/1$ mode [2, 11]. This suggests that the effect of the mode on plasma confinement has m number dependence and in particular, $m = 1$ mode close to the ideal stability limit has major impact to the equilibrium. As other experimental facts, this mode has been observed in the configuration with only $|B_t| \geq 0.75$ T. For example, in the configuration with $A_p = 8.3$ and $B_t = -0.5$ T, $m/n = 1/1$ mode has been observed as “rotating” mode which is similar to the mode shown in Fig.3 and 4. It does not cause a clear degradation of a plasma confinement, and achieved $<\beta_{dia}>$ is about 2.6 %. When there is no “non-rotating” mode, “rotating” MHD modes are dominant in any A_p configuration. Especially, $m/n = 2/3$ mode where the resonance is near edge is clearly enhanced with increasing A_p. This fact suggests that the edge MHD activity is one of reasons why achieved beta decreases with increasing A_p. Unfortunately, there is no information on the plasma rotation in the experiments. Such kind of measurement makes the relationship between the rotation and the growth of the mode clear from a viewpoint of the stabilization effect on the mode.

Acknowledgements

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