MHD Activities in high-β regime of LHD

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1. Introduction

An understanding of MHD characteristics in high-β plasma is a main subject in toroidal devices for a realization of a fusion reactor. Net-current free plasmas in stellarator-heliotrons are free from current-driven instabilities unlike in tokamaks, and characterization of pressure-driven modes and control of them in the high-β regime are one of crucial issues towards for a helical fusion reactor. Since the heliotron configuration has a magnetic hill in the peripheral region, violation of stability of ideal and resistive interchange modes are concerned. With regard to the modes with the resonance in the core region, stabilization due to spontaneous generation of magnetic well has been verified in the experiment [1]. In contrast, theoretical prediction suggests that low-n mode such as $m/n = 1/1$ which has a resonance around $\rho = 0.9$ limits the pressure gradient in the peripheral region and consequently determines the beta limit [2]. In previous experiments in LHD, MHD modes excited in the peripheral region have been observed even in the low-β regime, and amplitudes of the modes such as m/n = 2/3 mode are considerably enhanced in the H-mode plasma with steep edge pressure gradient [3]. Since there are the several low-n rational surfaces in the peripheral region, activities of their resonant modes are a key issue for higher-β plasma production.

Since Large Helical Device (LHD) experiments were started in 1998, plasma parameters have been improved with progress of heating power systems during every experimental campaign. In recent experiments, the maximum averaged beta value $<\beta_{dia}>$ of 4 % was obtained by high power neutral beam heating of up to 12 MW in the configuration with $R_{ax} = 3.6$ m, $B_t = 0.45$ T and $n_e \sim 2.5 \times 10^{19}$ m^{-3}, where R_{ax} and B_t are magnetic axis position and toroidal magnetic field at R_{ax}, respectively. The $<\beta_{dia}>$ is the diamagnetic beta value defined as $4\mu_0/3 \cdot W_{dia}/(B_{av0}{}^2 V_{p0})$, where W_{dia} is the diamagnetic energy. The 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. This article presents MHD characteristics in the extended β regime.

2. Typical high-β discharge and MHD analysis

Figure 1 shows typical MHD activities in typical high-β discharge. The R_{ax} and Bt are set at 3.6 m and 0.5 T, respectively. The pitch parameter of helical coil γ is 1.22, which has high aspect ratio compared with the standard configuration with γ = 1.25. Three neutral beams are injected to this plasma and the deposition power is about 6.9 MW at 1.725 s. The m/n = 1/1, 2/3 and 2/5 modes excited in the edge region are dominantly observed in this discharge. The m/n = 1/1 and 2/3 modes grow from 0.7s and their amplitudes increase with

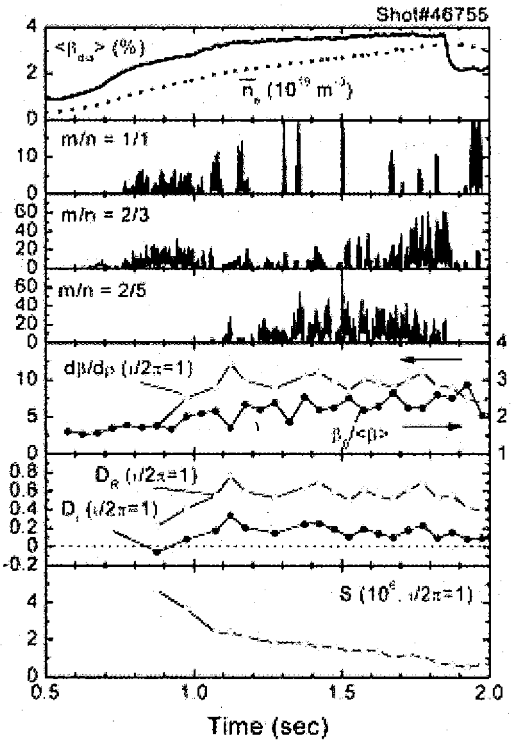

Figure 1 Temporal changes of plasma parameters in high-β discharge.

$<\beta_{dia}>$. However, when $<\beta_{dia}>$ exceeds a certain value at 1 s, the m/n = 1/1 mode is frequently interrupted and the amplitude of m/n = 2/3 mode starts to decrease. Then $<\beta_{dia}>$ starts to increase suddenly, and the amplitude of the m/n = 2/5 mode increases after that. At 1.73 s, the degradation of $<\beta_{dia}>$ occurs with the growth of the m/n = 2/3 mode and the reduction of the m/n = 2/5 amplitude, although the heating and the supply of H_2 gas are still maintained. The equilibrium reconstruction and stability analysis are done for this discharge by 3-D MHD equilibrium code VMEC, and the result on m/n = 1/1 mode is shown in fig.1 as the example. While the pressure gradient around the m/n = 1/1 resonant surface increases with $<\beta_{dia}>$ and saturates at 1.1 s, the peaking

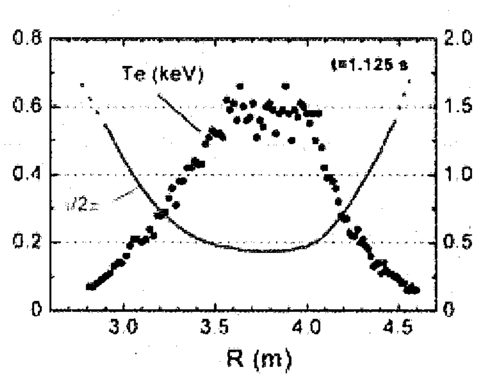

Figure 2 Te and iota profiles at 1.125 s in fig.1 discharge.

factor of pressure profile increases till one NBI is turned off. The Mercier parameter D_I, which is well used as the index of high-n ideal stability, indicates the mode is unstable because of the reduction of magnetic shear due to finite-β effect. The low-n ideal mode is expected to be stable because the D_I is less than 0.2. The D_R is the index of resistive interchange stability, and positive D_R means the resistive mode is still unstable during the discharge. The magnetic Reynolds number S, which is related with the linear growth rate of resistive interchange mode, decreases with increasing $\langle\beta_{dia}\rangle$, and this suggests the rise of the growth rate of the mode. These results are inconsistent with the suppression of the m/n = 1/1 mode. Figure 2 shows the Te and iota profiles at 1.125 s in fig.1 discharge. The flattening structures of Te profiles are found, for example, near the m/n = 1/1 resonant surface. These asymmetrical structures are well observed in high-β discharges, and however, it is difficult to apply such profiles to the present the equilibrium reconstruction. This flattening contributes the stabilization of the ideal and resistive modes. One of possibilities for the formation of the asymmetrical profile in periphery is due to variation of magnetic surfaces due to finite-β effect such as the generation of the magnetic island.

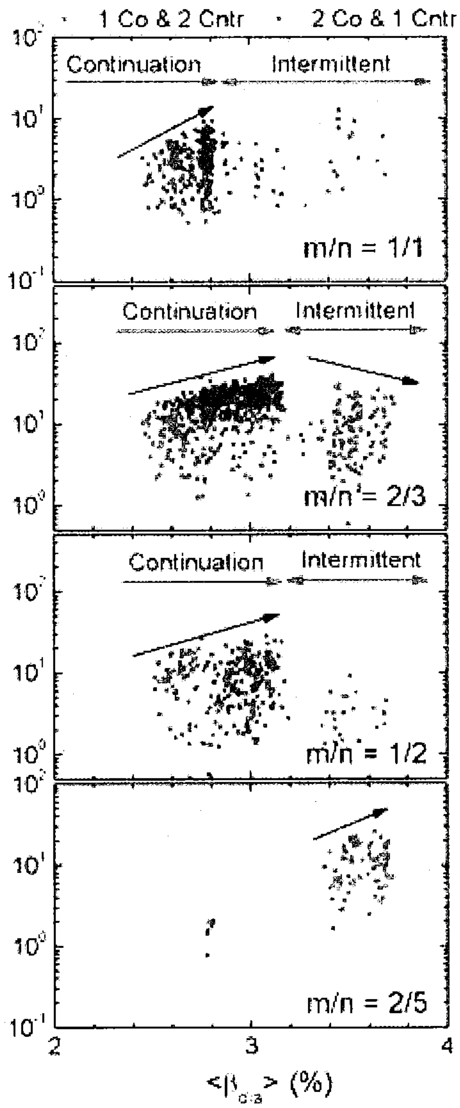

Figure 3 β dependence of MHD modes

2. β dependence of MHD modes and plasma shift due to finite-β effect

Figure 3 shows changes of the amplitudes of observed MHD modes as a function of $\langle\beta_{dia}\rangle$ in γ = 1.22 configuration. Although the m/n = 2/1 mode excited in core region has been observed in the $\langle\beta_{dia}\rangle$ rage of less than 2.5 % in previous experiments, this mode disappears in the high-β regime. The resonant surfaces with $\iota/2\pi \geq 1$ are located at $\rho \geq 0.9$ and their resonant modes are dominantly observed in the $\langle\beta_{dia}\rangle$ range with more than 2.5 %. While the amplitude of the m/n = 1/1 mode increases with $\langle\beta_{dia}\rangle$, it disappears or is intermittently observed when $\langle\beta_{dia}\rangle$ exceeds 2.8 %. Although the changes of the amplitudes of m/n = 2/3 and 1/2 modes are similar to the case of m/n = 1/1 mode, the threshold $\langle\beta_{dia}\rangle$ where the mode disappears is higher. The m/n = 2/5 mode appears when $\langle\beta_{dia}\rangle$ exceeds 3.4 %, the amplitudes still increase with $\langle\beta_{dia}\rangle$ in the present $\langle\beta_{dia}\rangle$ range. These phenomena suggest that the *stable* region is expanded from inner region to outer one. The destabilization of the MHD mode just outside the "*stable*" region may be caused by the steep pressure gradient outside the profile flattening as shown in fig.2.

The magnetic axis shift ΔR_{ax} identified by Te profile measured with Thomson scattering system is about 0.25 m at 1.725 s in fig.1 discharge, and this corresponds to $\Delta R/a \sim 0.25$. The statistical analyses indicate that this shift is smaller by about 50 % than the standard configuration with $\gamma = 1.25$. One of the reasons is that the rotational transform in $\gamma = 1.22$ is higher than the standard case, which leads to a restriction of Shafranov shift. Central rotational transforms in $\gamma = 1.22$ and $\gamma = 1.25$ in vacuum are 0.33 and 0.45, respectively. Although the reduction of the shift restricts the formation of magnetic well from the centre of plasma, it takes advantage from a viewpoint of beta-limit due to MHD equilibrium. Also, it contributes to prevent the reduction of the heat deposition of neutral beams because the direction of NBI is optimized to magnetic configuration with R_{ax} = 3.6~3.7 m. Therefore, the high-aspect-ratio configuration may be suitable for high-β plasma production from viewpoints of the power deposition. On the other hand, the variation of magnetic field structure may be an essential issue for the production of higher-β plasma rather than the R_{ax} shift itself from a viewpoint of equilibrium β-limit.

As a summary, several MHD modes in periphery are excited and spontaneously stabilized in turn when β increases, which may suggest an expansion of the MHD *stable* region of the plasma. The profile flattening has been observed in high-β regime, and it contributes the stabilization of MHD modes. The careful reconstruction of the equilibrium with applying asymmetrical profile is required for understanding of the mechanism of the mode stabilization.

References

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