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Relationships between the Prediction of Linear MHD Stability Criteria and the Experiment in LHD

WATANABE Kiyomasa Y., NARUSHIMA Yoshiro, SAKAKIBARA Satoru, OHDACHI Satoshi, TOI Kazuo, COOPER Antony W.[1], NAKAJIMA Noriyoshi, NARIHARA Kazumichi, TANAKA Kenji and LHD experimental group

National Institute for Fusion Science, Toki 509-5292, Japan

[1]Centre de Recherches en Physique des Plasmas, Association Euratom / Confederartion Suisse, EPFL, 1015 Lausanne, Switzerland

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Abstract

We analyze the relationship between the experimentally observed pressure gradients at resonant rational surfaces and the theoretically predicted ideal magnetohydrodynamics (MHD) unstable region of global modes in the large helical device (LHD). According to the stability analysis of the ideal MHD modes with a low toroidal mode number, we find that the ideal MHD mode gives a constraint on the operational regime of the pressure gradients in the core. In the edge, a clear saturation of the pressure gradients due to the ideal MHD instability has not been observed up to the high beta regime around 3% as the volume-averaged toridal beta value, where global ideal MHD modes are predicted to be unstable.

Keywords:

heliotron, MHD stability, beta limit

1. Introduction

Heliotron device is a probable candidate of toroidal magnetic confinement systems as thermonuclear fusion reactor under steady-state operation because it can confine plasma with only external coils and install the well-defined divertor configuration. However, it is theoretically predicted that it has a disadvantage for pressure driven magnetohydrodynamics (MHD) instabilities, which may limit the operational regime of the plasma parameters such as beta, pressure gradient and/or so on [1]. In tokamaks, it is well known that the operational beta limits are quite consistent with theoretical predictions of ideal linear MHD theory [2]. On the contrary, in helical plasmas, the MHD instability effects on the operational beta range have not been clear. A limited number of experimental researches about the effect of pressure driven MHD instabilities on the operational beta range in heliotron devices have been reported, for examples, on Heliotron DR [3] and the compact helical system (CHS) [4]. There is difference of results in the previous works. The experimentally achieved beta is consistent with the beta limit theoretically predicted by a low-n (m/n = 5/4) ideal MHD instability in Heliotron DR. On the contrary, the discharges are maintained in unstable region predicted by low-n ideal MHD stability calculations in CHS. Here m and n are the poloidal and toroidal mode number of fluctuations, respectively. In the above previous works, they paid attention to an averaged beta, not to pressure profile so much in studying the operational regime. The stability of pressure driven MHD depends on the pressure gradients at their resonant rational surfaces. Moreover the pressure gradient and a net toroidal current affect the stability of pressure driven MHD modes through the change of MHD equilibrium in finite beta, for example, Shafranov shift, magnetic well formation and so on. This type of change in MHD equilibrium becomes significant in the devices with low aspect ratio and/ or low rotational transform like CHS and the Large Helical Device (LHD) [5]. In order to clarify the role of pressure driven MHD instabilities on operational regime, it is necessary to analyze the relationship between the unstable condition of the pressure driven MHD modes and the experimentally observed pressure gradients at every resonant rational surface based on the consistent MHD equilibrium with the measured profile data like density, temperature and current of plasmas.

LHD is a heliotron device, where the experiments started in 1998. The device major radius is 3.9 m, and the plasma minor radius is 0.64 m in a typical operation [5]. The aspect ratio, A_p and the central rotational transform, ι_0 are fairly close to CHS (A_p ~ 5 and ι_0 ~ 0.3). The Reynolds numbers in LHD

Corresponding author's e-mail: kiyowata@LHD.nifs.ac.jp

plasmas are larger by two orders than those in the medium sized heliotron devices such as CHS [6]. It is considered that the ideal pressure driven MHD mode plays an important role in MHD properties, in especially core region. In the early phase of LHD experiments, high beta discharge over 2% was achieved in an unfavorable magnetic configuration for MHD stability with inwardly shifted vacuum magnetic axis, R_{ax} = 3.6 m [6]. Recently, we obtain higher beta plasma around 3% at the low field operation of 0.5 T in unfavorable configurations on MHD stability, the R_{ax} = 3.6 m configuration, without obvious degradation of the global energy confinement [7]. In this paper, in order to study the role of ideal pressure driven MHD modes on the operational regime in LHD, we compare the experimentally observed pressure gradients at resonant rational surfaces with the theoretically predicted unstable region for ideal pressure driven MHD instabilities in the R_{ax} = 3.6 m configuration, carefully taking account of the toroidal current effects.

2. Experimental setup

LHD has powerful measurement systems of profiles; for example, electron temperature profiles are measured at over 100 radial positions by Thomson scattering measurement [8], which leads to the detailed comparative analysis between experiment and calculation. We consider the m/n = 2/1 and 1/1 modes as typical low-n MHD unstable modes at the core and edge region, because the rational surfaces of 1/2 and 1/1 modes exist at ρ = 0.5 and ρ = 0.9, respectively, in the R_{ax} = 3.6 m configuration. Here ρ is a radial variable. ρ^2 is proportional to the toroidal flux and it is equal to unity at a plasma edge. Experimental beta profile is estimated under an assumption that it is proportional to electron pressure profile. Electron pressure profile is product of electron temperature by Thomson scattering measurement and electron density by FIR measurement. Volume averaged beta $\langle\beta\rangle$ is defined as $\langle\beta\rangle \equiv (2/3)(W_p/V_p)(B_{av}{}^2/2\mu_0)$. Here W_p is the plasma stored energy by a diamagnetic measurement and μ_0 is the permeability in vacuum. V_p and B_{av} are the plasma volume and the volume-averaged toroidal magnetic field strength in vacuum, respectively. The high beta discharges in LHD are maintained by NBI (Neutral Beam Injection), where a finite net toroidal current is observed due to bootstrap current and Ohkawa current [9]. The net toroidal current is measured by the Rogowskii coil loop. Up to now, however, we dot not have a technique to measure the toroidal current profile, so that we use a model current profile in the following calculations.

3. Relationships between the prediction of linear MHD stability and the experiment

Figure 1 shows the experimentally observed pressure gradients at ρ = 0.5 in the R_{ax} = 3.6 m configuration in $\langle\beta\rangle$-dβ/dρ diagram under (a) co- and balanced NBI, and (b) cntr.-NBI. Here β is a local beta value estimated by the volume-averaged toroidal magnetic field strength. The data were obtained in 0.5 T to 1.5 T operation. Circles in Fig. 1(a)

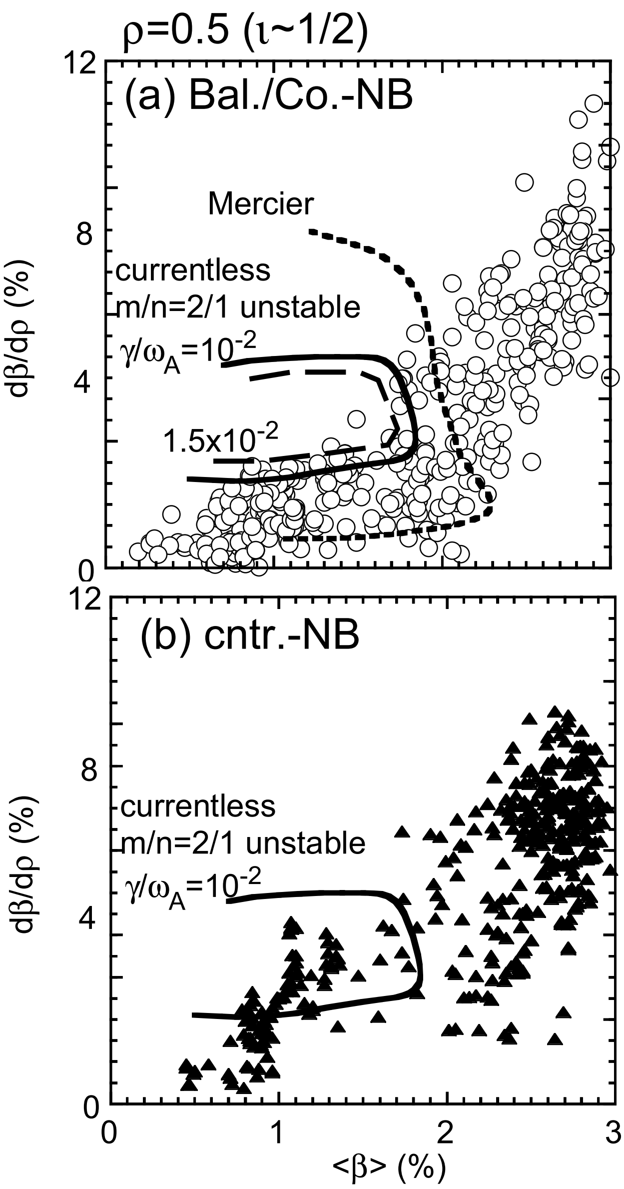

Fig. 1 Pressure gradients observed experimentally at ρ = 0.5 (core) in the R_{ax} = 3.6 m configuration in $\langle\beta\rangle$-dβ/dρ diagram under (a) co- and balanced-NBI, and (b) cntr.-NBI. The theoretical prediction based on low-n (m/n = 2/1) ideal pressure driven MHD mode under currentless plasma is shown by solid and dashed lines.

correspond to the observed pressure gradients under co- and balanced NBI. Observed net toroidal current is 0~25 kA/T, where the 1/2 rational surfaces exist. Because the positive toroidal current makes worse the stability condition than currentless cases, the currentless condition for MHD equilibria gives an upper limit of the stability condition in the discharges under co- and balanced NBI. Solid and dashed lines in Figs. 1 and 2 denote the contours of the growth rate of low-n (m/n = 2/1 and m/n = 1/1) ideal MHD modes (with global mode structure), $\gamma_{low\text{-}n}/\omega_A$ = 10^{-2} and 1.5×10^{-2}, for currentless equilibria. The growth rate is calculated by a MHD stability analyzing code (TERPSICHORE [10]) for various assumed pressure profiles. Here $\omega_A = v_{A0}/R_0$, v_{A0} and R_0 are

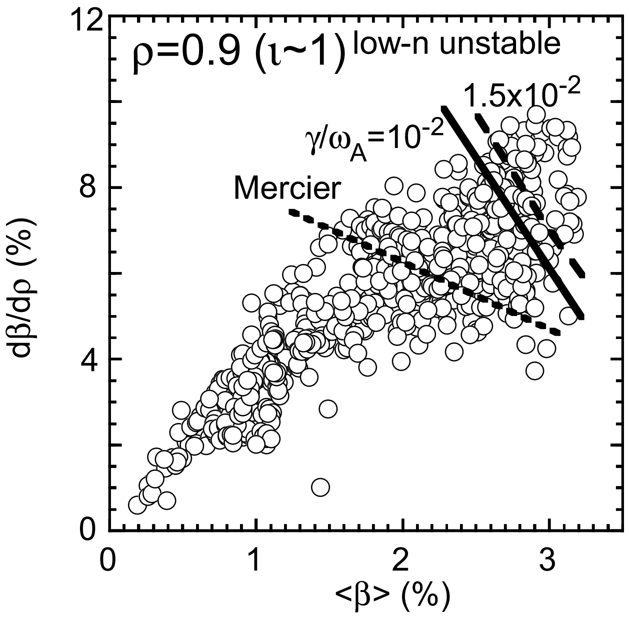

Fig. 2 Pressure gradients observed experimentally at ρ = 0.9 (edge) in the R_{ax} = 3.6 m configuration in $\langle\beta\rangle$-dβ/dρ diagram.

the Alfven velocity and the major radius at the magnetic axis. The dotted lines are the stability boundary of Mercier modes (with a highly localized mode structure / high-*m* limit) [11]. The maxima of the achieved pressure gradients seem to saturate against the contour of $\gamma_{low\text{-}n}/\omega_A = 1.5 \times 10^{-2}$ in the intermediate beta range of 1~1.8%. When $\langle\beta_{dia}\rangle$ exceeds ~1.8%, the maximum of the pressure gradient more than doubles. These experimental observations coincide with violation of low-*n* modes and stabilization due to spontaneous generation of a magnetic well due to the Shafranov shift.

Triangles in Fig. 1(b) correspond to the observed pressure gradients under cntr.-NBI, where the observed net toroidal current is –6~8 kA/T. According to a numerical analysis [9], the bootstrap current is estimated to be about 13 kA at $\langle\beta\rangle$ = 1.8% and 0.75 T. Therefore, we should carefully treat the effect of the toroidal current on MHD equilibria and stabilities. We use a model toroidal current profile as

$$j = j_1*(1-\rho^2)^2 + j_2*(1-\rho^2)*\rho^2, \tag{1}$$

where 1st and 2nd terms are considered as the Ohkawa current ($j_1 > 0$ under co-NB and $j_1 < 0$ under cntr-NB) and bootstrap current ($j_2 > 0$), respectively [9]. In eq. (1), we assume the bootstrap current 13.3 kA/T (10 kA at 0.75 T), which is independent of $\langle\beta\rangle$ for simplification, and determine such j_1 as the net toroidal current is –6 kA/T, which is the minimum of the observed toroidal current. Under cntr.-NBI, the Shafranov shift at edge is suppressed by positive toroidal current and that at core is enhanced due to negative toroidal current, which leads to deeper magnetic well formation and larger magnetic shear in core region comparing with the equilibrium with monotonic negative toroidal current profile in spite of low net toroidal current. As a result, the theoretically predicted unstable region disappears in $\langle\beta\rangle$-dβ/dρ diagram. Under cntr.-NBI, even below $\langle\beta\rangle$ = 1.8%, the experimentally observed pressure gradients exceed the upper limit of those under co- and balanced NBI. The deposition profiles under co- and cntr.-NBI are almost same in the R_{ax} = 3.6 m configuration. According to observation of magnetic fluctuation, m/n = 2/1 mode is dominant comparing with higher harmonic modes like m/n = 4/2. These experimental results suggest that the global ideal MHD modes limit the operational regime through the pressure gradient limit in the core region nevertheless the achieved pressure gradients reach the global ideal MHD unstable region with $\gamma_{low\text{-}n} = 1.5 \times 10^{-2}\ \omega_A$.

In Fig. 2, the observed pressure gradients at ρ = 0.9 exhibit slight saturation with the beta increase. However, the clear saturation of the pressure gradients in the edge has not been observed in the global MHD unstable region. Nevertheless, the achieved pressure gradients are more deeply in the unstable region compared with results in the core. These results from Figs. 1 and 2 suggest that a criterion based on linear MHD analyses, where the ideal MHD instabilities affect the operational regime, depends on the plasma parameters such as the magnetic shear or the magnetic Reynolds number, which are quite different in between the core and the edge. As another possibility, the beam pressure effect is considered to explain the reason why the effect of the ideal MHD instability on the local pressure gradients is different in between the core and the edge. In low field operation, where the high beta discharges are operated, the beam pressure is probably large. The qualitative estimation of beam pressure effects is one of our future research topics. As another approach to make clear whether global ideal MHD modes limit the pressure gradients in the edge like in the core, it is considered that the observed pressure gradients could be extended to other magnetic configurations. This is also an important subject for study.

4. Summary and discussion

We study the role of ideal MHD modes on the operational regime with high beta discharges in LHD by comparing between the experimentally observed pressure gradients and the theoretically predicted unstable region of ideal pressure driven MHD modes. Low-*n* (n = 1) ideal pressure driven MHD instabilities give a constraint on the operational regime of the pressure gradients at the core region and in the intermediate beta range of 1~1.8%. Even for the same vacuum configuration, the net toroidal current conditions together with the pressure profile significantly change the ideal MHD stability through the variation of MHD equilibria. The freedom of the pressure and the toroidal current profiles extends the operational regime, which may lead to achievement of high beta discharges under the unfavorable magnetic configuration for MHD stabilities like the R_{ax} = 3.6 m configuration in LHD experiments. However, there are a lot of low order rational surfaces in addition to ι =

1/2 and 1. Since Mercier modes do not affect the operational regimes (see Figs. 1 and 2), it is considered that there is an upper limit of the wave number of the ideal MHD modes, which affects the operational beta range and the pressure gradients. Here we analyze the operational beta range based on the ideal MHD theory. We know that the observed pressure gradients are in the nonlinear saturation phase. However, since it has not been clear how the pressure driven MHD instability affects the experimental operation regimes of the helical systems, our approach (evaluating the experimentally achievable pressure gradients by the linear growth rate and/or Mercier parameter) would be useful, because it could be a reference for more complicated nonlinear analyses, and a criterion for a reactor design.

We analyze only gas-puffing discharges in order to study the condition on the operational regime achieved in stationary. In the transient state like as just after pellet injection, the minor internal disruption with the saw-tooth-like fluctuation is observed [12], and the observed pressure at core gradients exceed the boundary of low-n (m/n = 2/1) ideal MHD stability [13], shown by lines in Fig. 1. Up to now, such state is not maintained in stationary though it does not go to a major disruption.

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