J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 214–217

MHD Stability of Low-*n* Ideal External Mode in Large-Helical-Device Plasma

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(Received: 10 December 2003 / Accepted: 25 April 2004)

Abstract

The characteristics of low-*n* ideal external modes in the Large-Helical-Device are studied. The low-*n* analysis is carried out with the TERPSICHORE code [W.A. Cooper, Plasma Phys. Control. Fusion **34**, 1011 (1992)]. Under fixed boundary conditions, the low-*n* instability region is limited within the Mercier unstable region and the external mode does not appear. On the other hand, with free boundary conditions, the low-*n* unstable region spreads and the external modes become unstable. The effects of a conducting wall similar in shape to that of the plasma show that stability to external modes of higher growth rate can be obtained even with the wall further away from the plasma.

Keywords:

ideal MHD, LHD, external mode, conducting wall, TERPSICHORE

1. Introduction

Recent magnetohydrodynamics (MHD) studies in the Large Helical Device (LHD) experiment show that MHD activity clearly appears around the peripheral region of high β plasmas [1]. The LHD plasma is generated and stably maintained even in Mercier unstable regions. This shows that the high-*n* mode does not affect the LHD plasma (Here, *n* is the toroidal mode number). The magnetic measurement clearly indicates that the low-*n* mode fluctuation originated from a pressure gradient driven instability. In general the low-*n* interchange mode structures spread across to the whole plasma, while the high-*n* mode structures are narrow, which means that the low-*n* mode has much more spatial effect on plasma. Therefore, we focus on the low-*n* mode in this study.

Although serious MHD instabilities leading to the termination of the discharge have not been observed, it is worthwhile to investigate the characteristics of the MHD activities in the LHD plasma theoretically and experimentally. In this study, we focus on external modes (particularly m/n = 1/1 mode) which occurs near the peripheral region in LHD. A low-*n* ideal MHD analysis is performed for the n = 1 mode family in the LHD plasma using the three-dimensional stability code TERPSICHORE [2]. We will show the equilibrium and the method of analysis in the following section. The characteristics of the unstable region and the mode structures affected by the conducting wall are examined in Sec. **3**, and Section **4** will summarize these discussions.

2. Stability analysis and equilibrium

2.1 Equilibrium

The equilibria of LHD plasma are calculated with VMEC [3] with free boundary conditions. The pressure profile $p_{(\rho)}$ is assumed to be $p_{(\rho)} = p_0(1 - \rho^2)^{0.5}(1 - \rho^8)$ here, p_0 and ρ are the plasma pressure at the magnetic axis and normalized averaged minor radius, respectively. We examine the effect of the profile of the rotational transform, because the external mode is sensitive to the rotational transform at the edge $\iota_{(1)}/2\pi$ [4]. In the equilibrium calculation the various $\iota_{(1)}/2\pi$ are obtained by changing the position of the plasma surface and β [5].

2.2 Stability

Because we mainly examine the external mode (particularly m/n = 1/1 mode) in this study, the low-*n* ideal MHD analysis is performed for the n = 1 mode family in the LHD plasma using TERPSICHORE, which is able to calculate the stability under fixed and free boundary conditions. In the free boundary condition, various wall shapes can be prescribed. To examine the wall effect against the instabilities, the analysis of the stability is carried out with various walls that conform to the shape of the plasma. The

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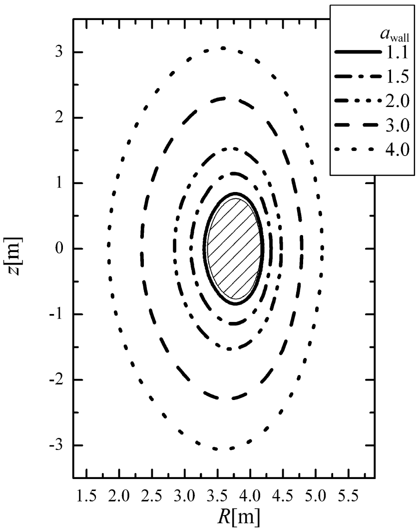

Fig. 1 Shapes of the conducting wall and plasma.

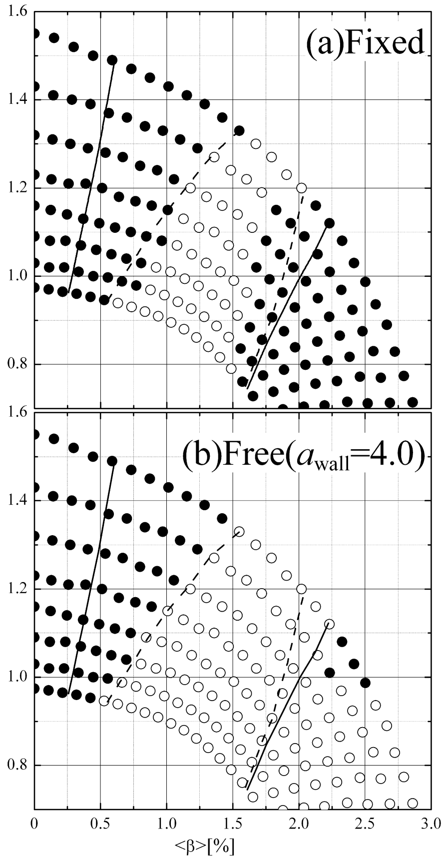

Fig. 2 Unstable region under (a) Fixed and (b) Free boundary conditions. Closed and open circle means the stable and unstable respectively. The solid and dashed contour lines indicate the Mercier parameter $D_I = 0$ and $D_I = 0.2$ at $\iota/2\pi = 0.5$, respectively.

parameter of the wall shape a_{wall} is defined as the ratio of the average radius of the wall to the average plasma radius. The range of a_{wall} adopted in this study is $1.0 < a_{wall} < 4.0$ (Fig. 1). Here, $a_{wall} = 1.0$ is equivalent to the fixed boundary condition.

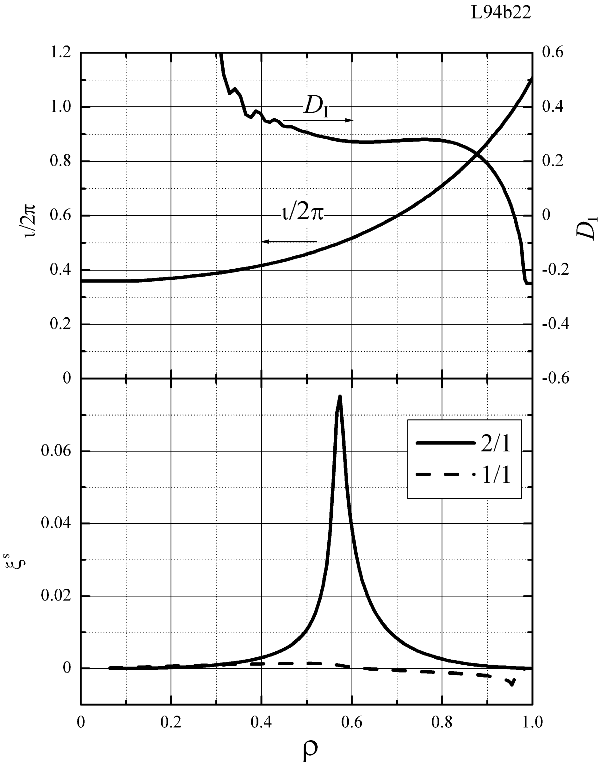

Fig. 3 Profile of the rotational transform $\iota/2\pi$, Mercier parameter D_I and Fourier amplitude under the fixed boundary condition. Solid, dashed and dotted lines mean the m/n = 2/1 and 1/1 mode respectively.

3. MHD Unstable region

The VMEC equilibrium points are plotted in the plane of beta vs. rotational transform at the plasma edge $\iota_{(1)}/2\pi$ in Fig. 2. The boundary conditions of the fixed (a_{wall} = 1.0) and free (a_{wall} = 4.0) are shown in Figs. 2(a) and 2(b), respectively. The open circles indicate growth rates $\gamma > 10^{-5}$, which is defined as unstable for the n = 1 mode. The solid and dashed contour lines indicate the Mercier parameter $D_I = 0$ and $D_I = 0.2$ at $\iota_{(1)}/2\pi = 0.5$, respectively.

3.1 Fixed boundary

As shown in Fig. 2(a), the n = 1 modes are destabilized within the Mercier unstable region with D_I (at $\iota/2\pi = 0.5$) > 0.2 regardless of the value of $\iota_{(1)}/2\pi$. A typical mode structure with the rotational transform and D_I profiles are shown in Fig. 3 for a plasma that has the parameters (β, $\iota_{(1)}/2\pi$) = (1.36%, 1.1). The m/n = 2/1 mode shows the peak at the resonant surface of $\iota/2\pi = 0.5$ within the Mercier unstable region, which displays the characteristic of an internal mode.

Under the fixed boundary condition, the m/n = 1/1 mode has a smaller Fourier amplitude than the 2/1 mode.

3.2 Free boundary

Under the free boundary condition, the low-n unstable area expands to encompass the part of the Mercier stable domain with $\iota_{(1)}/2\pi < 1.0$ which is mostly stable under fixed

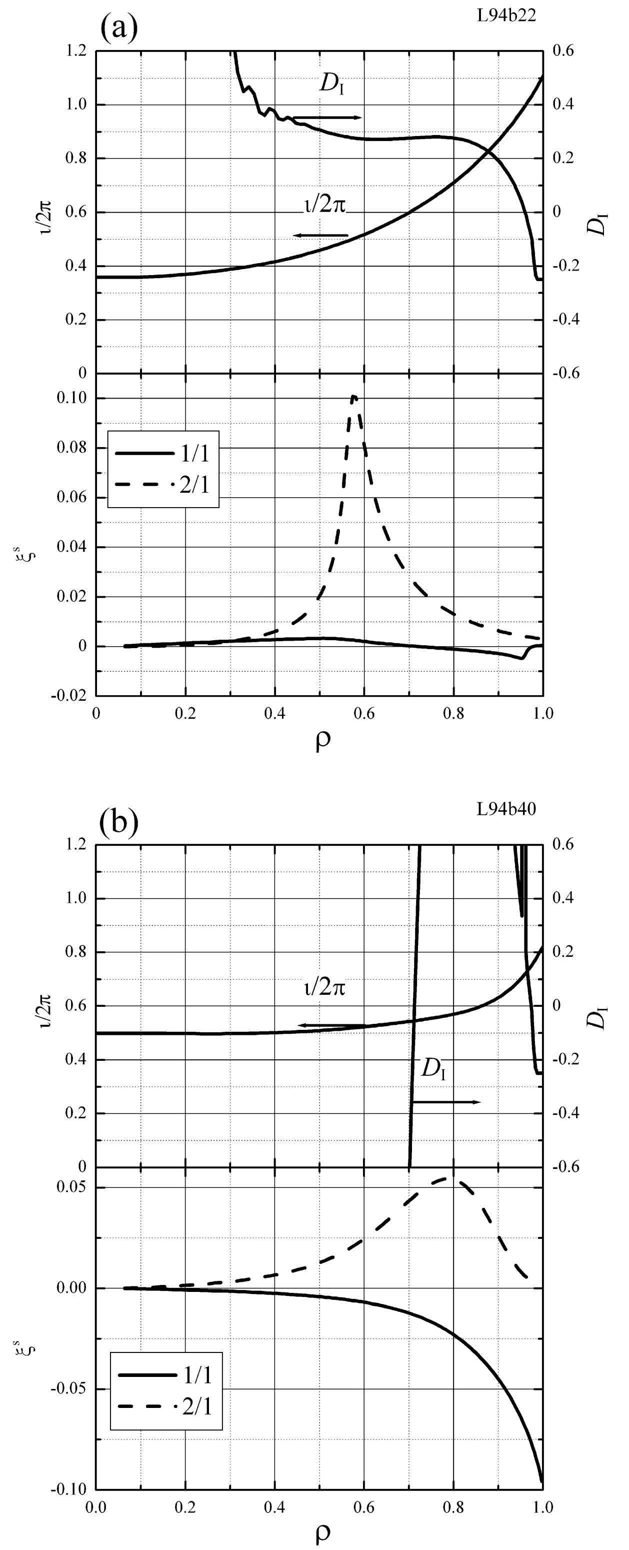

Fig. 4 Profile of the rotational transform $\iota/2\pi$, Mercier parameter D_I and Fourier amplitude under the free boundary condition. (a) $\iota_{(1)}/2\pi > 1.0$, (b) $\iota_{(1)}/2\pi < 1.0$.

boundary conditions (Fig. 2(b)). In the region of $\iota_{(1)}/2\pi > 1.0$, the low-*n* unstable area remains in the Mercier unstable region. Fig. 4(a) shows a typical mode structure in this area, which is similar to an internal mode under the fixed boundary condition.

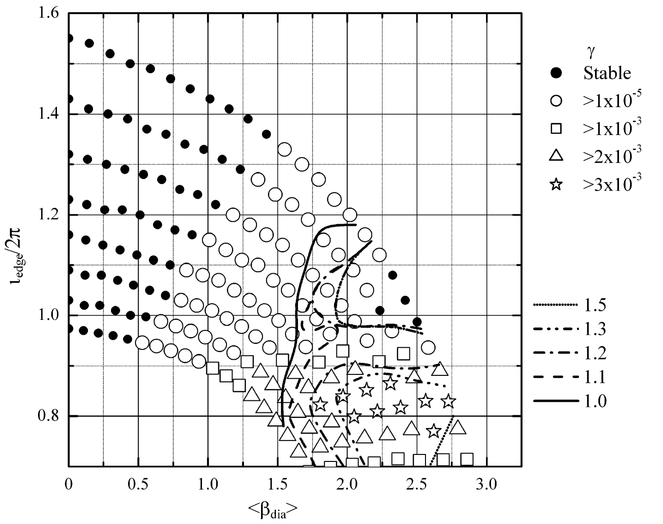

Fig. 5 Low-*n* unstable region modified by the conducting wall. The open symbols mean unstable. The circle, square, triangle, and star indicate the growth rates of $\gamma > 10^{-5}$, $\gamma > 10^{-3}$, $\gamma > 2 \times 10^{-3}$, and $\gamma > 3 \times 10^{-3}$, respectively. The dotted, double dot-dashed, dot-dashed, dashed, and solid lines indicate the boundary between the stable and unstable region at each wall position of a_{wall} = 1.5, 1.3, 1.2, 1.1, and 1.0 (fixed boundary), respectively.

In case of $\iota_{(1)}/2\pi < 1.0$, the expanded unstable region exists even in the Mercier stable region. The mode structure in this region clearly shows the characteristics of an external mode (Fig. 4(b)) in which the m/n = 1/1 mode remarkably appears. According to the toroidal mode coupling effect, the m/n = 2/1 component is also destabilized as a nonresonantly coupled mode when the resonance surface of $\iota_{(1)}/2\pi = 0.5$ does not exist.

3.3 Effect of the position of the conducting wall

The unstable region and mode structures depend on the position of the conducting wall. The change of the unstable region is shown in Fig. 5. The open symbols mean unstable. The circle, square, triangle, and star indicate the growth rate of $\gamma > 10^{-5}$, $\gamma > 10^{-3}$, $\gamma > 2 \times 10^{-3}$, and $\gamma > 3 \times 10^{-3}$, respectively. The dotted, double dot-dashed, dot-dashed, dashed, and solid lines indicate the boundary between the stable and unstable region at each wall position of a_{wall} = 1.5, 1.3, 1.2, 1.1, and 1.0 (fixed boundary), respectively.

The conducting walls change the unstable region when $\iota_{(1)}/2\pi < 1.0$. On the other hand, the boundary around the low-β region is not modified by the wall. The plasmas with higher growth rate of $\gamma > 10^{-3}$ are stabilized with a wall further away from the plasma. For example, almost all the points with $\gamma > 3 \times 10^{-3}$ (Star) plasmas are stabilized by the wall with a_{wall} = 1.3. Fig. 5 shows that the conducting wall position required to stabilize the external mode depends on the growth rate. The physical mechanism of this interesting phenomenon is the future work. The difference of the stabilizing behavior is shown in Fig. 6. The free boundary

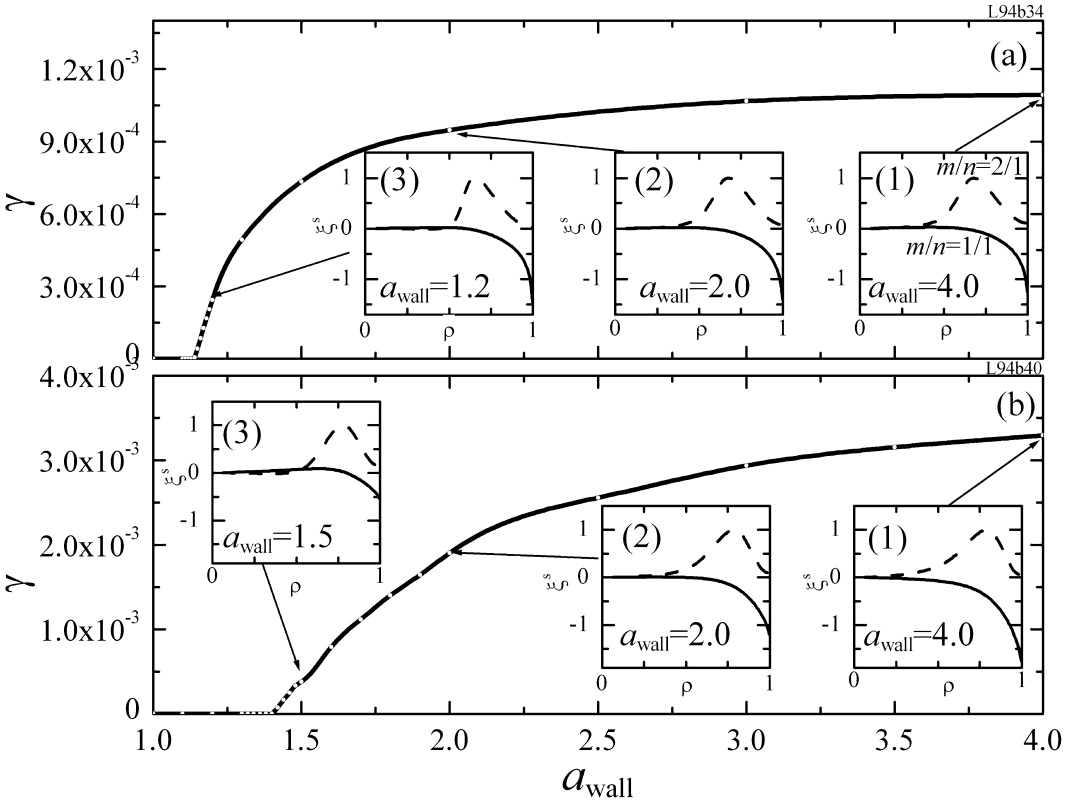

Fig. 6 Relationship between the a_{wall} and γ. In lower growth rate (a) γ=1.1 × 10^{-3}, mode structures do not significantly vary with a_{wall}. On the other hand, in higher growth rate (b) γ = 3.3 × 10^{-3}, the amplitude of the *m*/*n* = 1/1 mode component decreases in comparison with that of *m*/*n* = 2/1 mode component.

condition (a_{wall} = 4.0), the plasmas with (β, $\iota_{(1)}/2\pi$) = (1.9%, 0.96) and (2.2%, 0.81) have growth rates of $\gamma = 1.1 \times 10^{-3}$, and $\gamma = 3.3 \times 10^{-3}$ respectively. In the former case, the growth rate hardly decreases with the wall and reduces to zero at a_{wall} < 1.14 as shown in Fig. 6(a). The mode structures (*m*/*n* = 2/1 and 1/1) are also shown in Figs. 6(a)(1)–(3). These structures do not significantly vary with a_{wall}. On the other hand, the latter case (Fig. 6(b)) shows that a wall with larger effective radius remarkably reduces the growth rate and the plasma is stabilized at a_{wall} < 1.4. The wall modifies the mode structures (Figs. 6(b)(1)–(3)). The amplitude of the *m*/*n* = 1/1 mode component decreases in comparison with that of *m*/*n* = 2/1 mode component.

4. Summary

We have mainly examined the stability of external modes in the LHD plasma. The external mode occurs in equilibria without the resonant surface of $\iota/2\pi$ = 1.0 under the free boundary condition, which has *m*/*n* = 1/1 component. The internal mode (*m*/*n* = 2/1) remains in the Mercier unstable region under the fixed boundary condition. The conducting wall suppresses the external mode. In free boundary conditions, the growth rate and the mode structure change with wall positions at higher β and γ value, while they remain roughly constant at lower β and γ. The external mode is stabilized by the wall effect. However, the internal mode (*m*/*n* = 2/1) is not stabilized.

Acknowledgement

This study was supported by a Grant-in-Aid for Young Scientists(B)(No.15760627) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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