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Study of ideal external mode in LHD

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1. Introduction

Serious MHD instabilities leading to the degradation of the energy confinement time and the termination of the discharge have not been observed in experiment on the Large Helical Device (LHD) [1]. It is worthwhile to investigate the characteristics of the MHD activities in the LHD plasma theoretically and experimentally. In this paper, we focus on the external mode (particularly m/n=1/1 mode). The low-n ideal MHD analysis is performed for n=1 mode family on the LHD plasma using the three-dimensional stability code **TERPSICHORE** [2].

2. Characteristics of ideal MHD stabilities of LHD plasma at peripheral region

The analyzed plasma has the magnetic axis at R_{ax}=3.6m and no plasma current I_p=0. The plasma pressure p is expressed as $p=p_0(1-\rho^2)^k$. Here, p_0, ρ, and k are the central plasma pressure, normalized minor radius in flux coordinate, and the parameter of the profile with the range of 0.2 to 1.0, respectively. The equilibrium is solved by VMEC code [3] under the condition of the free boundary. Figure 1 shows low-n ideal MHD mode unstable region in <β> - dβ/dρ diagram for n=1 mode family. The all symbols mean the destabilized points with respect to the low-n interchange mode calculated by **TERPSICHORE** under the free boundary condition. The black, green and red lines

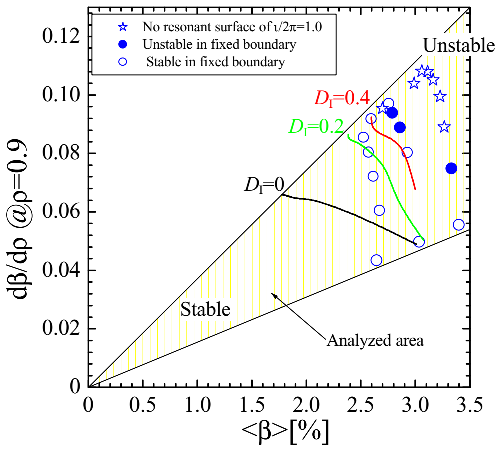

Fig. 1 Relation between the beta and the pressure gradient at ρ=0.9.

mean the contours of Mercier parameter [4] with D_I=0, 0.2, and 0.4, for ι/2π=1.0 resonant mode respectively. In the case of the fixed boundary condition, the points of the closed circle remain unstable, and the amplitude of the radial component of the displacement vector (ξ_s) at plasma boundary is zero ($\xi_{s(1)}$=0). This structure is defined as "internal mode" henceforth. In this case, the qualitative correlation between the D_I and low-*n* mode is found. On the other hand, under the free boundary condition, the domain of low-*n* unstable region expands wider in comparison with the fixed boundary condition. In typical LHD plasma with low-β, the ι/2π=1.0 and 0.5 resonance surfaces are inside plasma. However, ι/2π=1.0 surface disappears under high-β. The equilibrium shown by stars do not have the resonant surface of ι/2π=1.0. In this situation, the displacement vector at ρ=1.0 has the meaningful value and this mode structure is defined as "external mode" henceforth. The ξ_s profile of an external mode has a structure with a dominant *m*/*n*=1/1 contribution, as described in section 3.

3. Detail of mode structure and wall effect against the external mode

Figure2 shows an example of the mode structure of the external mode whose dominant mode is *m*/*n*=1/1. The pressure profile is assumed as $p=p_0(1-\rho^2)^{0.5}(1-\rho^8)$ and β=2.73%. This profile does not have the surface current originate from the pressure gradient at ρ=1.0. The rotational transform at plasma boundary ($\iota_{(1)}/2\pi$) is below 1.0 (Fig.2 (d)). As shown in Fig.2 (a), the components of *m*/*n*=2/1 and 1/1 mode appear together. The amplitude of ξ_s of the *m*/*n*=1/1 mode is maximum at ρ=1.0, where it locally indicates the tendency toward stability (D_I<0, dW>0, Fig.2(b)(c)). On the other hand, *m*/*n*=2/1 mode shows the off-resonant mode and its peak position is ρ=0.7. The potential energy at that position is positive that means the stability by *m*/*n*=2/1 mode.

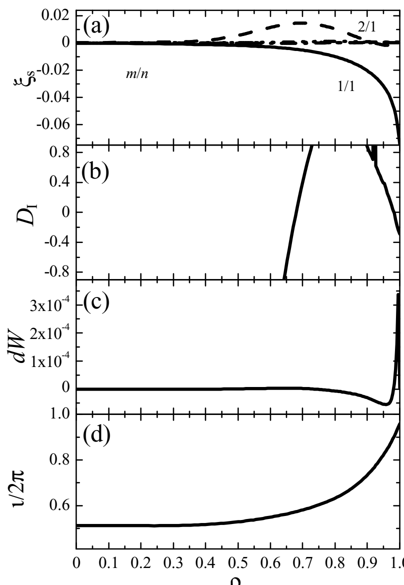

Fig. 2 The profile of (a)ξ_s, (b)D_I (c)dW, and (d)ι/2π.

The external mode is stabilized under the fixed boundary condition. **TERPSICHORE** is able to calculate the stability with various wall shapes. To examine the wall effect against the mode, the analysis of stability is carried out with the various walls whose shapes are similar figures of the plasma boundary. Figure 3 shows the wall effect on the external mode as the dependence of the eigenvalue on a_{wall} (the ratio of the averaged radius of the wall and the plasma boundary) with the range from 1.0 (fixed boundary) to 5.0. The growth rate is almost constant at a_{wall}>2.0, that is, the results are almost same as a free boundary condition. The eigenvalue decreases steeply with a_{wall} below a_{wall}<1.5, and finally, the external mode can be stabilized with a_{wall} <1.08. We also adopt a wall shape that is similar to the real LHD vacuum vessel shape. In this case, the eigenvalue is equal to the case of a_{wall}=3.0, which means the real LHD wall is equivalent to the case of a_{wall}=3.0 with regard to the m/n=1/1 mode so that the real LHD wall represents a nearly free boundary condition for ideal MHD stabilities.

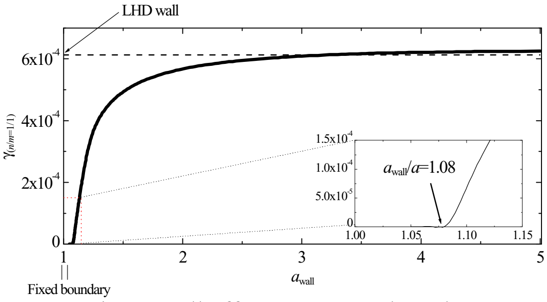

Fig. 3 Wall effect on external mode.

4. The domain where external mode appears

We focus on the effect of the profile of the rotational transform, especially the value at edge $\iota_{(1)}/2\pi$. Here, we also assume $p=p_0(1-\rho^2)^{0.5}(1-\rho^8)$. To obtain the equilibrium in various $\iota_{(1)}/2\pi$, the position of the plasma boundary is changed in the calculation with VMEC. One way to produce such plasma configuration experimentally is usage of a limiter [5]. The low-n unstable region under the free boundary condition is shown in Fig.4. The points of open and closed symbol mean low-n stable and unstable, respectively. In the unstable symbols, the closed circles mean the largest amplitude of ξ_s for m/n=2/1 modes and closed stars for 1/1 mode. The red solid and dashed lines indicates the contours of Mercier parameter with D_I=0, 0.2, for $\iota/2\pi$=0.5 resonant mode, respectively, and blue solid line indicates the contour of D_I=0 for $\iota/2\pi$=1.0 resonant mode. The contour of D_I=0.2 for $\iota/2\pi$=1.0 does not exist in this equilibrium region. The red symbols mean low-n unstable even in the fixed boundary condition and the modes are destabilized in the Mercier unstable region with D_I(@i/2π=0.5)>0.2 regardless of the value of $\iota_{(1)}/2\pi$. These mode structure shows the internal mode and the main component is m/n=2/1 mode (Fig4.(a)). Under the fixed boundary condition, there does not

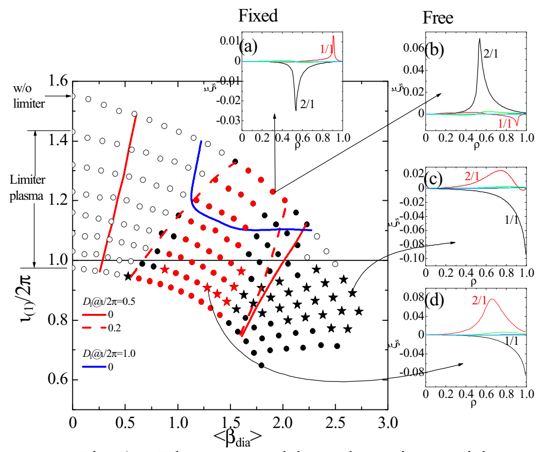

Fig.4 The unstable domain with respect to low-n mode.(n=1 mode family).

exist the mode structure in which the m/n=1/1 appears independently. Under the free boundary conditions, the low-n unstable area is expanded to Mercier stable and $\iota_{(1)}/2\pi>1.0$ region more widely than the case under the fixed boundary condition. In case of $\iota_{(1)}/2\pi>1.0$, the low-n unstable area stays in Mercier unstable region and the mode structure is similar to an internal mode (Fig.4 (b)). In case of $\iota_{(1)}/2\pi<1.0$, on the other hand, the unstable region exists even in Mercier stable region and the mode structure clearly shows the characteristics of an external mode (Fig.4 (c)). In this case, the amplitude of m/n =1/1 becomes larger than that of m/n=2/1. At the region with Mercier unstable and $\iota_{(1)}/2\pi<1.0$, the mode structure has the comparable amplitude of ξ_s of m/n =2/1 and 1/1 (Fig.4 (d)). These show that the structure of an external mode, which has the meaningful m/n =1/1 mode, appears in the region of $\iota_{(1)}/2\pi<1.0$ regardless of the value of D_I under the free boundary condition.

4.Conclusion

The low-n analysis for n=1 mode family is performed on the LHD plasma. The analysis with **TERPSICHORE** predicted that the external mode with m/n=1/1 would be unstable in the high beta region. The external mode structure, which has the m/n=1/1 mode, appears under the free boundary and $\iota_{(1)}/2\pi<1.0$. The perfectly conducting wall of $a_{wall}<1.08$ stabilizes the external mode. The real LHD wall is equivalent to the a_{wall}=3.0, which is almost free boundary condition. The region where external mode appears lies under the condition of the free boundary and $\iota_{(1)}/2\pi<1.0$, even in Mercier stable and/or low-β region. If the condition with no rational surface of $\iota/2\pi$=1.0 inside the plasma can be produced, the external mode could be studied experimentally.

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