IDEAL AND RESISTIVE INTERCHANGE INSTABILITIES IN NEGATIVE SHEAR TOKAMAKS AND CURRENTLESS HELIOTRON PLASMAS

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Abstract

For tokamaks the *ideal* localized interchange mode does not play a role for q (safety factor) > 1 in the whole plasma region, while it becomes unstable in the edge region with a magnetic hill in heliotron plasmas. However, for negative shear tokamaks, the *resistive* localized interchange mode becomes unstable when q_0 is much larger than q_{min}, where $q_0(q_{min})$ is a central (minimum) q value. It is also shown that *ideal* and *resistive* non-resonant global interchange modes appear easily in the central region of heliotron and in the negative shear tokamak, which are similar to the infernal mode in the low-shear tokamak.

1. INTRODUCTION

The interchange mode is easily destabilized for finite pressure plasmas when the magnetic curvature is unfavorable. For a circular cross-section tokamak the ideal interchange mode is unstable for $q(r) < 1$ [1], when q is a safety factor and r denotes a radius. For stellarators, however, there is no such a universal condition. The stability of ideal interchange mode is determined by competition between the destabilizing force due to pressure gradient and the stabilizing effects due to magnetic shear and magnetic well. The property of Mercier criterion for heliotron devices has been clarified from the relation between low-n and high-n modes [2], where n is a toroidal mode number. It is known that the interchange mode becomes more unstable with finite resistivity, since the stabilization of magnetic shear disappears. Although there are already many works for the interchange modes in tokamaks and stellarators, we show new results related to the interchange mode for both negative shear tokamaks [3], [4], [5] and currentless heliotron plasmas [6].

2. MHD EQUILIBRIUM AND STABILITY ANALYSES

For calculating the MHD equilibrium of negative shear tokamak, we assume a safety factor profile as shown in *FIG. 1.* The parameters for describing the noncircular cross-section are the same as given by Freidberg [7]. The MHD equilibria are calculated with VMEC code developed for three-dimensional MHD equilibria in stellarators [8]. The local MHD stability was examined with the GGJ stability criteria [9],

$$D_I = E + F + H - \frac{1}{4} < 0 \tag{1}$$

for the ideal MHD modes, and

$$D_R = E + F + H^2 < 0 \tag{2}$$

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*National Institute for Fusion Science, Oroshi, Toki, Japan 509-5292 for the resistive MHD modes. Here E, F and H are the same quantities given by GGJ. It is noted that the criterion (1) can be written as

$$D_R = D_I + \left(H - \frac{1}{2}\right)^2 < 0 \ . \qquad (3)$$

Therefore, the resistive MHD modes will be easily destabilized in configurations with large values of $|H - 1/2|$. The linear stability against global ideal and resistive interchange modes can be examined with RESORM code which has been also developed for heliotrons [10]. Since this stability analysis is based on the averaged approach [2], it is easy to apply the RESORM code to tokamaks, since a single toroidal mode number n can be assigned even in heliotrons. Thus MHD equilibrium and stability are analyzed with two numerical codes VMEC and RESORM in this paper.

3. RESONANT INTERCHANGE MODES IN NEGATIVE SHEAR TOKAMAKS

Stability criteria for both the local ideal and resistive interchange modes, (1) and (2), are examined for negative shear tokamaks. The safety factor profile for MHD equilibria are shown in *FIG. 1.* For these negative shear configurations the resistive interchange modes becomes unstable [10], while the ideal interchange modes are stable, since $q(r) > 1$ everywhere. However, it is found that the resistive interchange modes have a significant stabilizing tendency by making the plasma cross-section elliptic. When the ellipticity κ becomes large, the beta limit β_c given by $D_R = 0$ increases. For highly elliptic tokamaks, the Troyon coefficient β_N is shown in *FIG. 2*, which gives an average beta limit by $\beta_N I_p(\mathrm{MA})/(a(\mathrm{m})B_T(\mathrm{T}))$, where I_p is a plasma current, a is a minor radius and B_T is a toroidal field. Although β_N has a peak at $\kappa = 1.6$ due to the increase of I_p, $\beta_c(0)$ increases monotonically; $\beta_c(0) = 1.7\%$ at $\kappa = 1$ and $\beta_c(0) = 4.9\%$ at $\kappa = 2$. The triangularity also suppresses the resistive interchange instability. When the local stability criterion predicts instability, low-n resistive interchange modes usually become unstable as shown in *FIG. 3* and *FIG. 4*. *Figure 3* shows the growth rate normalized with the poloidal Alfvén transit time τ_A as a function of the toroidal mode number n for $\beta(0) = 4\%$. For $3 \leq n \leq 6$, the ideal mode is stable. In *FIG. 4*, the radial mode structure of $n = 3$ resistive interchange mode is shown. It is localized at the resonant surface $q = 8/3$. This kind of global instability may be dangerous for the lowest rational value of q in the negative shear region. It is the hollow plasma current to destabilize the resistive interchange modes through $(H - 1/2)^2$ in the criterion (3). In heliotron plasmas, the resistive interchange modes become unstable due to the magnetic hill in the outer negative shear region.

4. NON-RESONANT INTERCHANGE MODES IN HERIOTRON PLASMAS WITH HIGHLY PEAKED PRESSURE PROFILES AND NEGATIVE SHEAR TOKAMAKS

Here our interest is in the low shear region near the magnetic axis, since one way to suppress the resistive interchange mode in the tokamak is to reduce the negative magnetic shear or make q_0 close to q_{min}. It is noted that the magnetic shear is also weak in the central region of heliotron configuration. It has been shown that the non-resonant interchange modes are destabilized near the magnetic axis for a resistive plasma with a highly peaked pressure profile in H-E [11]. The non-resonant mode becomes more unstable, when $q(0)$ is closer to the low-order resonant value. It has a ballooning-like mode structure in the toroidal plasma.

Recently same non-resonant low-n interchange modes are found for Heliotron E with the ideal MHD model, when $q(0) \lesssim 2$ [12]. Its characteristic is similar to the

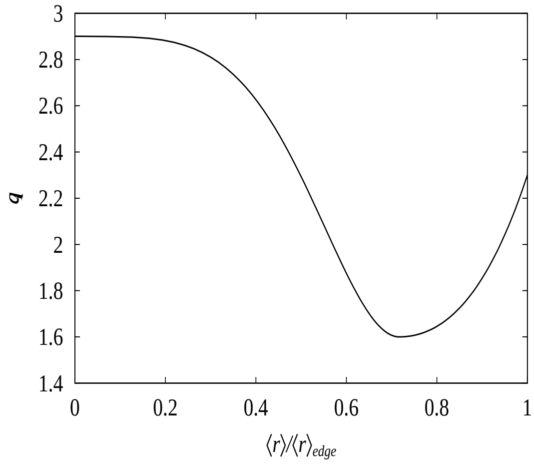

FIG. 1: Safety factor profile of negative shear tokamak.

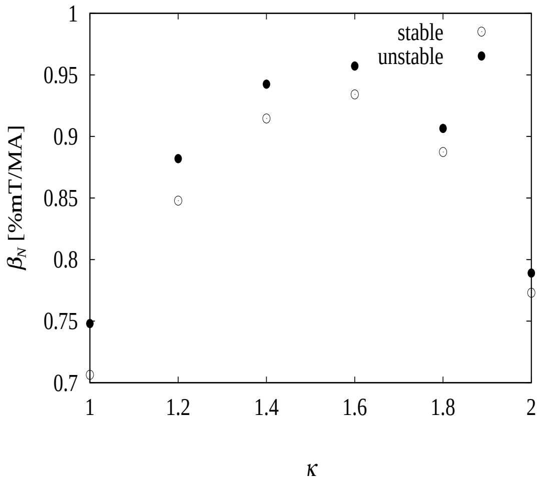

FIG. 2: Dependence of β_N *on* κ *at the beta limit for the q-profile in FIG. 1. Pressure profile is assumed* $P = P_0(1-\Phi)^2$*, where* Φ *denotes a toroidal flux function.*

infernal mode in the low shear tokamaks [13] as shown in *FIG. 5*, and this mode may be involved in the internal disruption appeared in the central region of Heliotron E [14]. For heliotron plasmas, the stability of interchange modes is crucial to eliminate the disruptive behavior and obtain the higher beta plasmas. It is noted that the ideal modes shown in *FIG. 3* for the negative shear tokamak are classified as non-resonant ones. The radial mode structure of $n = 1$ non-resonant ideal mode is shown in *FIG. 6*. Thus one significant property of MHD stability in both negative shear tokamaks and heliotron plasmas is appearance of non-resonant mode.

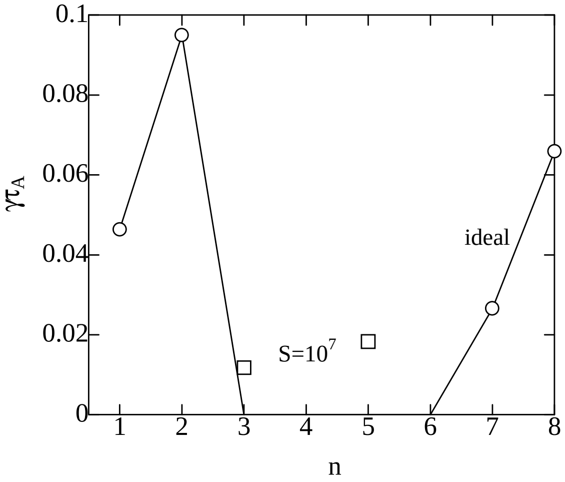

FIG. 3: Growth rates of low-n modes for the circular negative shear tokamak with q-profile shown in FIG. 1. Here $\beta(0) = 4\%$*. For* $n = 3$ *and* $n = 5$*, growth rates of resistive modes with* S *(magnetic Reynolds number)* $= 10^7$ *are also shown. All other cases belong to the ideal modes.*

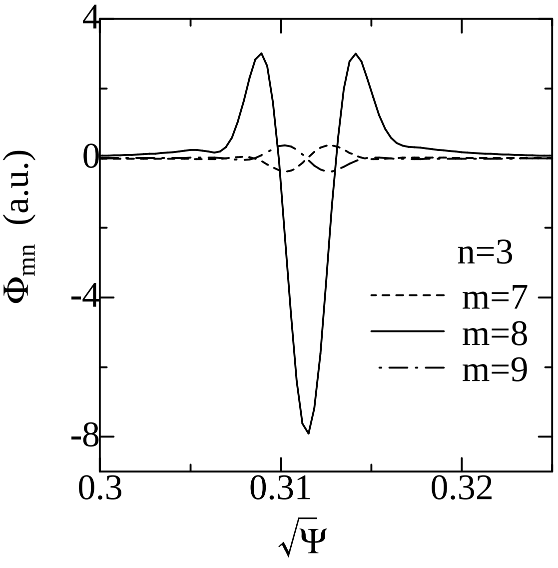

FIG. 4: Radial mode structure of $n = 3$ *mode with* $S = 10^7$ *and* $\beta(0) = 4\%$*. The growth rate of this mode is shown in FIG. 3.*

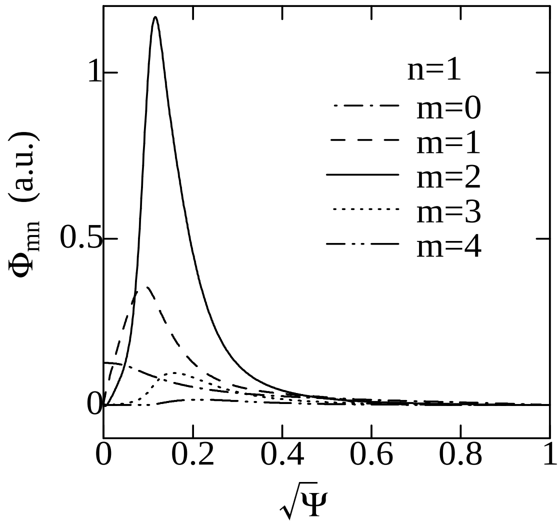

FIG. 5: Radial mode structure of $n = 1$ *non-resonant ideal mode in Heliotron E for* $\beta(0) = 1\%$ *and* $P = P_0(1-\Psi)^{10}$, *where* Ψ *denotes a poloidal flux function. The growth rate is* $\gamma\tau_A = 0.047$.

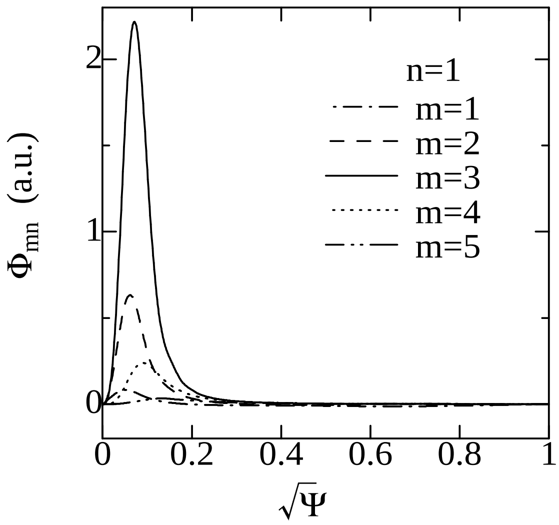

FIG. 6: Radial mode structure of $n = 1$ *non-resonant ideal mode for* $\beta(0) = 4\%$. *The growth rate of this mode is shown in FIG. 3.*

5. DISCUSSION

It is pointed out that the resistive interchange modes becomes unstable in the negative shear tokamaks when q_0 is larger than q_{min}; however, they may be suppressed by optimizing non-circularity of plasma cross-section and q-profile. The beta limit due to the resistive interchange modes is lower than the ideal kink-ballooning beta limit. Thus, it is expected a soft beta limit will be seen in experiments when the resistive interchange modes become unstable. For both the negative shear tokamaks and heliotron plasmas, it is shown that non-resonant ideal interchange modes become unstable, which are similar to the infernal mode in the low shear tokamak.

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