IDEAL AND RESISTIVE LOCAL MHD INSTABILITY IN NEGATIVE SHEAR TOKAMAKS

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Abstract

Resistive local MHD modes become unstable in negative shear tokamaks, although ideal ones are stable for $q \gtrsim 1$. When ellipticity (κ) and triangularity (δ) are increased at a fixed central beta value, resistive local MHD modes have stabilizing tendency and become marginal at $\kappa \gtrsim 1.8$ even for $\delta \simeq 0$. Also low aspect ratio negative shear tokamaks are favorable for stabilizing these modes.

1. Introduction

Recent topic in the tokamak research is the negative magnetic shear (or reversed magnetic shear) configuration[1,2] for improving plasma confinement and making it possible to obtain a stationary operation with a high bootstrap current. From experimental results the negative shear region with $q' < 0$ and velocity shear of toroidal flow near the minimum surface of safety factor q with $q' = 0$ are ingredients for generating the internal transport barrier which contributes to the confinement improvement[3]. Here our concern is in the MHD stability in the negative shear region, since the high performance of the negative shear configuration will be limited by the behavior of unstable MHD modes[4]. Experimentally magnetic fluctuations were observed when $q_{\rm min}$ decreases. The limiting value seems $q_{\rm min} \gtrsim 2$; however, $q_{\rm min} \sim 1.5$ was realized in some cases.

In Section 2 MHD equilibria for negative shear tokamaks are discussed first. Then the stability criteria for both ideal and resistive local MHD modes are shown, which were obtained by Glasser, Greene and Johnson (GGJ)[5]. In Section 3 it is shown that the resistive local modes become unstable in the negative shear region of a circular cross-section tokamak. The stabilizing tendency given by non-circularity such as ellipticity and triangularity is also shown. The negative shear configuration in low aspect ratio tokamaks is examined for improving the stability. Concluding remarks are given in Section 4.

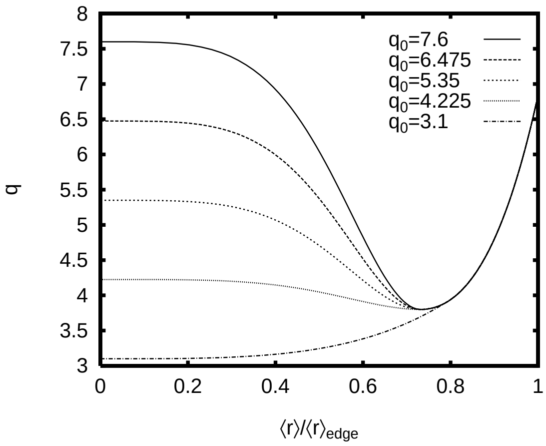

Figure 1. q profiles in the equilibrium calculations. The horizontal axis label is the normalized plasma minor radius.

2. MHD Equilibrium and Local Stability

For calculating the MHD equilibrium of negative shear tokamak, we assumed several safety factor profiles as shown in Fig.1. The parameters for describing the non-circular cross-section are the same as given by Freidberg[6]. The MHD equilibria were calculated with VMEC code developed for three-dimensional MHD equilibria in stellarators[7]. The pressure profile is assumed $P = P_0(1 - \Phi_T)^2$, where Φ_T denotes a toroidal flux function. The local MHD stability was examined with the GGJ stability criteria[5],

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

for the ideal MHD modes, and

$$D_R = E + F + H^2 < 0 \quad (2)$$

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

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

Therefore, the resistive modes will be easily destabilized in configurations with large values of $|H - 1/2|$.

3. Local MHD Stability for Negative Shear Tokamaks

The ideal local MHD stability criterion (1) is the same as the Mercier criterion[8], which gives that the negative shear tokamak is stable for $q_{\min} \gtrsim (0.9 - 1.5)$. It should be noted that the specific marginal value of $q_{\min}$ depends on the ellipticity, κ, and the triangularity, δ. Thus there is no significant difference between the normal and negative shear case for ideal interchange modes.

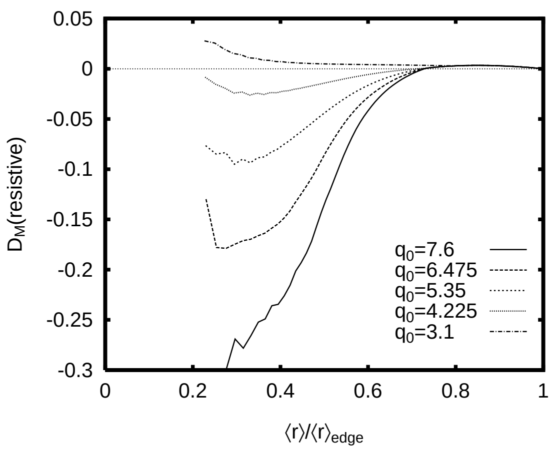

Figure 2. D_M dependence on q_0 for the circular tokamak with $A = 3$ and $\beta(0) = 3\%$ (or $\bar{\beta} \simeq 1.13\%$ and $\beta_N \simeq 3.1$).

It is found that the resistive local MHD modes become unstable in the negative shear region of circular tokamak with an aspect ratio 3 even for $q_{\min} > 1.0$ as shown in Fig.2. Here $D_M = -(\iota\!\!-)^2 D_R$ is plotted as a function of average radius at $\beta(0) = 3\%$, and $D_M > 0$ is necessary for stability. The rotational transform is denoted as $\iota\!\!-$. It is noted that the case with $q_0 = 3.1,\ \ \bar{\beta} = 1.13\%$ and $\beta_N = 3.1$ is stable. Here $\bar{\beta}$ is an average beta value and $\beta_N = \bar{\beta} a B_T / I_P$, where B_T is a toroidal field and I_P is a plasma current. The resistive local modes are destabilized with the increase of q_0 at a fixed $q_{\min}$ (see Fig.1). This tendency is understandable by checking the contributions from $(H-1/2)^2$ and D_I to D_R separately. When q_0 increases, the contribution of $(H-1/2)^2$ overcomes that of $D_I(<0)$ in the negative shear region.

Figure 3 shows the effect of elliptic deformation of flux surfaces on D_R with keeping the safety factor profile in Fig.1. When $\kappa \gtrsim 1.8$, the resistive local modes becomes stable even for $\delta = 0$ at $\beta(0) = 3\%$. Figure 4 shows the effect of triangular deformation of flux surfaces on D_R at $\kappa = 1.6$. The stability is improved with the increase of δ. The stabilizing or destabilizing tendency for changing κ or δ are also understandable by checking the contributions from $(H-1/2)^2$ and D_I to D_R separately. It is also found that the decrease of aspect ratio improves the stability to the resistive local modes as shown in Fig.5. Here the safety factor profile and the vacuum toroidal field at the plasma center are kept constant.

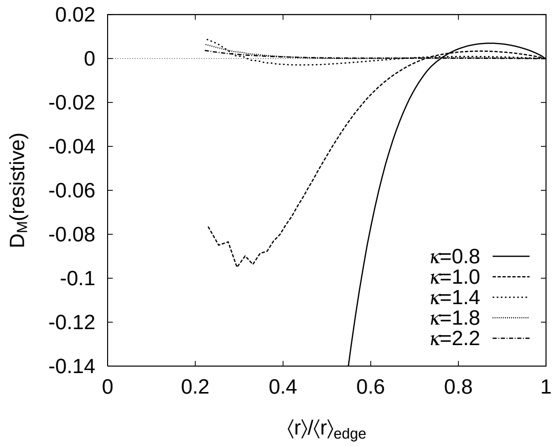

Figure 3. D_M dependence on κ for the elliptic tokamak with $A = 3$ and $\beta(0) = 3\%$. q profile is fixed at $q_0 = 5.35$ in Fig.1. Here, stable cases are ($\kappa = 1.8$, $\bar{\beta} = 1.08\%$, $\beta_N = 2.17$) and ($\kappa = 2.2$, $\bar{\beta} = 1.07\%$, $\beta_N = 1.70$). Unstable cases are ($\kappa = 0.8$, $\bar{\beta} = 1.15\%$, $\beta_N = 3.22$), ($\kappa = 1.0$, $\bar{\beta} = 1.13\%$, $\beta_N = 3.13$), and ($\kappa = 1.4$, $\bar{\beta} = 1.11\%$, $\beta_N = 2.72$).

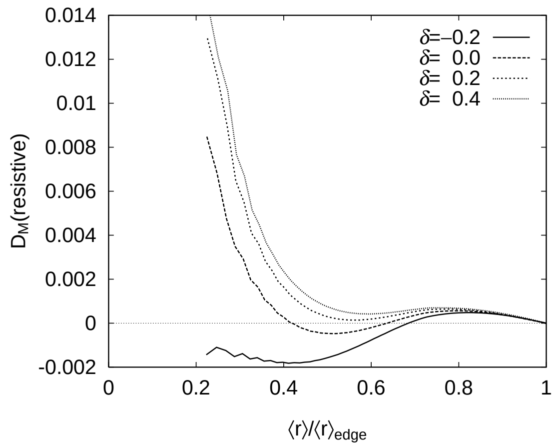

Figure 4. D_M dependence on δ for the non-circular tokamak with $A = 3$, $\kappa = 1.6$, and $\beta(0) = 3\%$. q profile is fixed at $q_0 = 5.35$ in Fig.1. Here, stable cases are ($\delta = 0.2$, $\bar{\beta} = 1.10\%$, $\beta_N = 2.27$) and ($\delta = 0.4$, $\bar{\beta} = 1.11\%$, $\beta_N = 2.09$). Unstable cases are ($\delta = -0.2$, $\bar{\beta} = 1.09\%$, $\beta_N = 2.53$) and ($\delta = 0.0$, $\bar{\beta} = 1.09\%$, $\beta_N = 2.45$).

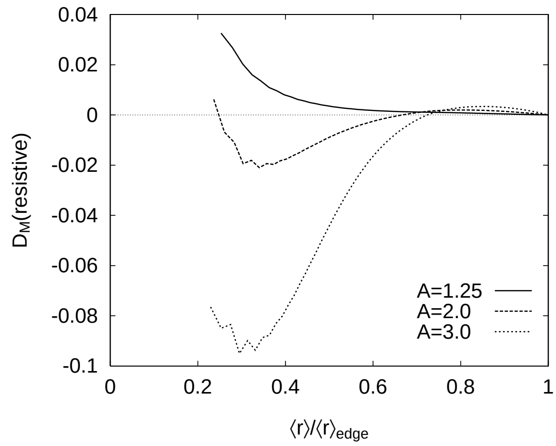

Figure 5. D_M dependence on A for the circular tokamak with $\beta(0) = 3\%$. q profile is fixed at $q_0 = 5.35$ in Fig.1. The stable case is ($A = 1.25$, $\bar{\beta} = 1.27\%$, $\beta_N = 0.72$), and unstable cases are ($A = 2.0$, $\bar{\beta} = 1.18\%$, $\beta_N = 2.03$) and ($A = 3.0$, $\bar{\beta} = 1.13\%$, $\beta_N = 3.13$).

Figure 6 shows that there exists the marginal value $\beta_N \sim 1$ for destabilizing the resistive interchange modes in the case of circular tokamak with $q_0 = 5.35$. It should be noted that the marginal $\beta(0)$ or β_N depends on the characteristics of MHD equilibrium.

4. Concluding Remarks

In negative shear tokamaks, the resistive interchange modes become unstable with the increase of plasma pressure. It is considered that global resistive modes at the low order resonant surfaces appear, when the local resistive stability criterion D_R is violated, from results for stellarators and heliotrons[9]. On the other hand, since the plasma temperature is high in the negative shear region, the FLR effect may stabilize the local MHD mode. Since the toroidal flow with velocity shear observed near the internal transport barrier is not included in the present analysis, it is necessary to study the toroidal shear flow effect on the MHD modes[10].

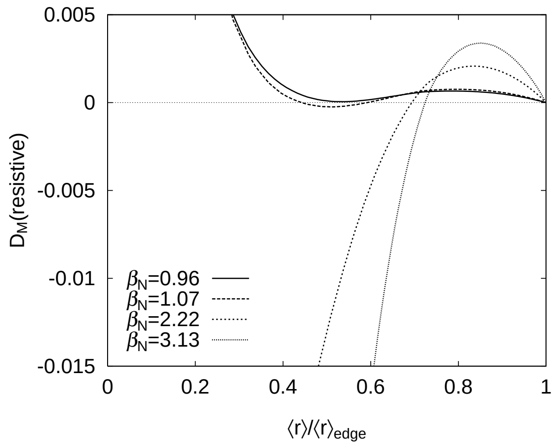

Figure 6. D_M dependence on β_N for the circular tokamak with $A = 3$. q profile is fixed at $q_0 = 5.35$ in Fig.1. Equilibria with β_N above 1.0 become unstable.

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