IMPROVEMENT OF MHD STABILITY IN NEGATIVE/WEAK SHEAR CONFIGURATIONS FOR A STEADY STATE TOKAMAK

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Abstract Comprehensive stability analyses have been carried out to clarify characteristics of MHD stability of both strongly negative and weak shear configurations for improvement of plasma performance. Hard beta limits due to ideal MHD stability can be improved by reducing the pressure gradient in the weak shear region and by increasing the pressure gradient near the plasma surface in both configurations. In the negative shear configuration, the double tearing mode may emerge just under $q_{min}=2$. However, small current modulation, to reduce the shear, at the outer resonance surface stabilizes the double tearing mode. In the weak shear configuration, the neoclassical tearing mode, which is induced by the helical bootstrap current along the island, reduces the beta limit below the ideal kink limit. However, a localized additional current at the O-point of the island significantly stabilizes the mode. Stabilization of the KBM requires a large shear, which may be either positive or negative. A narrow stable window appears near null shear and expands with the pressure gradient.

1. INTRODUCTION

Two promising configurations can be considered for a steady state tokamak with a large bootstrap current. One is a strongly negative magnetic shear configuration exploiting a large bootstrap current, and the other is a weak shear configuration which utilizes a moderate bootstrap current and external current drive at the core. Whether a given configuration can achieve and sustain enhanced plasma performance critically depends on its MHD stability. In the negative shear configuration, the low-n kink mode can be stabilized by strongly negative magnetic shear. However, the ideal/resistive interchange modes become destabilized, and the double-tearing mode may be induced due to adjacent rational surfaces. Furthermore, when the intrinsic ion magnetic drift resonance is taken into account, a kinetic ballooning mode (KBM) emerges even in negative shear. On the other hand, in weak magnetic shear configuration, the neoclassical tearing mode persists an in positive shear, imposing a lower beta limit than that of the kink mode. So far, these MHD modes have been analyzed individually. In this work, an attempt is made to seek stable domain in high beta negative and weak shear tokamak discharges through comprehensive stability analyses.

2. IDEAL MHD STABILITY

Hard beta limit disruptions observed in high performance negative shear tokamak plasmas may be attributed to the kink-ballooning mode. When the radial position of the maximum pressure gradient is inside the q_{min} surface (q_{min} is the minimum of the q value), the infernal mode with $n\geq2$ and the high-n ballooning mode become stable, and the ideal beta limit is governed by the internal $n=1$ kink mode. For further improvement of the beta limit, increasing the edge pressure is effective. As shown in Ref. 1, the normalized beta value β_N as large as 2.5 - 3.5 can be realized for $q_{min}<2$. Here, the analysis of the low n mode was made for parameters pertinent to JT-60 configuration, $\varepsilon=0.25$, $\kappa=0.15$, $\delta=0.25$, without the wall stabilization, using ERATO-J code. The beta limit imposed by the kink mode in negative shear is improved by an increase in the value of q_0/q_{min}. However, the ideal/resistive interchange mode can be unstable for higher central q value if $q_{min}<2$ and reduces the beta limit. These localized modes limit the maximum pressure gradient at the internal transport barrier produced in the negative shear region.

ßp collapses observed in high performance weak shear plasma are also attributed to the kink-ballooning mode. The detailed analysis[2] for high ßp plasmas shows that broadening of the pressure profile combined with a high internal inductance, li, significantly increases the stability limit β_N (~5). The high li profile is produced by large shear near the plasma edge and weak shear near the plasma center. The possibility to produce the high li plasma with a self-consistent profile of the pressure and large bootstrap current has been indicated[3].

3. RESISTIVE MHD STABILITY

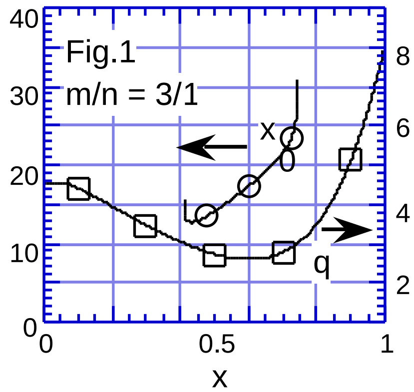
Negative shear tokamak discharge was thought to be unstable due to the occurrence of the double tearing mode. The ideal MHD stability analysis indicates the beta limit is improved in the region of $q_{min}<2$, therefore, it is important to investigate the stability of the double tearing mode around the $q=2$ rational surface. The double tearing mode and/or the double magnetic islands bridging two rational surfaces at different radii also emerge and impose a soft beta limit.

To analyze the double tearing mode, first, we construct solutions of the Newcomb equation, $L\xi(x)\equiv(f(x)\xi(x)')'-g(x)\xi(x)=0$, in a cylindrical plasma between the two rational surfaces with the help of the associated eigenvalue problem[4]: $L\xi(x)=-\lambda\rho(x)\xi(x);\rho(x)\rightarrow\rho_{0j}(x-x_j)^2+$, $\rho_{0j}>0$ as $x\rightarrow x_j (j=1,2)$; $0<x_1<x_2<a$; $'\equiv d/dx$, $\xi(a)=0; f(x_1)=f(x_2)=0$. Let $\xi_0(x)$ be the eigenfunction with the minimum eigenvalue $\lambda_0>0$. A global solution $y(x)$ for the Newcomb equation is a linear combination of $\xi_1(x), \xi_2(x)$ and

$$y(x) \rightarrow c_1(x-x_1)^{-1/2-\mu_1} + \left(\Delta_{1R}c_1 + \Gamma_{21}c_2\right)(x-x_1)^{-1/2+\mu_1},\ x \rightarrow x_1,$$

$$y(x) \rightarrow c_2(x_2-x)^{-1/2-\mu_2} + \left(\Delta_{2L}c_2 + \Gamma_{12}c_1\right)(x_2-x)^{-1/2+\mu_2},\ x \rightarrow x_2,$$

where c_1, c_2 are arbitrary constants, Δ_{1R}, Δ_{2L} are matching data, and Γ_{21}, Γ_{12} are coupling constants between the two magnetic islands at x_1, x_2. The eigenvalue λ_0 and the eigenfunction $\xi_0(x)$ play the important role in the resistive MHD stability in a negative shear configuration. The coupling coefficients, Γ_{21}, Γ_{12}, between the two magnetic islands at x_1, x_2 are proportional to $1/\lambda_0$, but are strongly asymmetric; $|\Gamma_{12}|<<|\Gamma_{21}|$ since $\xi_0(x)$ is large near x_2 as shown in Fig.1. This tendency is stronger for higher m modes (Fig.2(a),(b)). A slight increase in the distance between the rational surfaces decouples the islands for $m\geq3$ modes because of large values of λ_0, and weakening the magnetic shear at the rational surfaces is an effective stabilizing mechanism of the modes. The coefficients destabilizing the island at x_2, Γ_{21} and Δ_2', remain large for the $m=2$ mode, therefore, the reduction of Δ_2' by a current modulation at x_2 effectively stabilizes the double tearing mode.



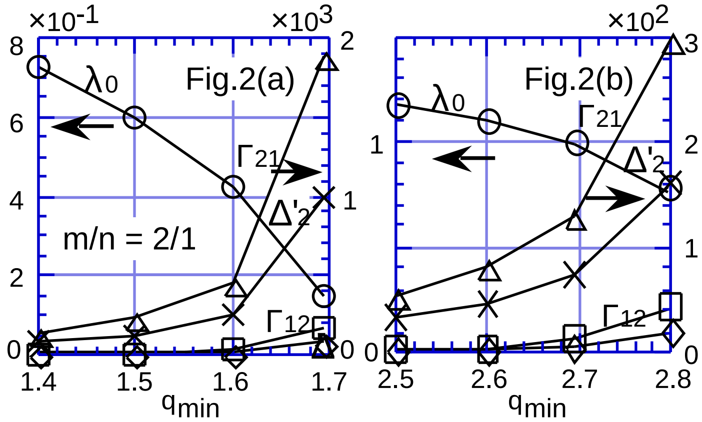


Fig.1 Eigenfunction between two rational surfaces for m=3 mode (q_{min}=2.6).

Fig.2 Dependence of the eigenvalue and matching data for (a) m=2 and (b) m=3 modes.

Three dimensional equilibrium analysis has also been performed using the PIES code[5] to study possible magnetic field configurations and q profiles in the stage of nonlinear saturation of the double tearing mode. When the initial value of q_{min} is slightly lower than the rational surface of 2, the saturated double island chains at the two rational surfaces are not well separated and the q profile becomes flattened slightly above $q=m/n$ as seen in Fig. 3a. However, when the difference between q_{min} and m/n exceeds a critical value, an equilibrium with $q_{min}<m/n$ can be realized without a flattened q profile bridging the two rational surfaces (Fig. 3b). The boundary of q profile flattening and no flatting regions is maybe lower than the ideal MHD stability boundary in the regime of $1.95<q_{min}<2$, as shown in Fig.4. Results indicate that it may be difficult to realize a configuration with $q_{min}<2$ and the possibility of the disruption by the double tearing mode around $q_{min}\sim2$.

In a low collisionality plasma with high ßp, large bootstrap fraction and long pulse lengths, neoclassical tearing modes will play a more prominent role in limiting stored energy and degrading confinement. The self-consistent effects of perturbed bootstrap currents allow pressure-induced magnetic island formation in the positive shear regions. Especially, a weak shear and large pressure gradient enhances the growth of the neoclassical tearing mode. The present stability analysis is based on the following saturated island equation (dw/dt=0), which is derived by the island evolution equation [6,7].

$$w_{sat} = \frac{4.63\sqrt{\varepsilon}\ L_q/L_p}{\frac{2}{\pi}\frac{\mu_0 R}{sB_p}\frac{I_{aux}}{\delta_J^2} - \Delta'(w_{sat})}$$

Here, ε is the inverse aspect ratio, $Lq=q/q'$, $Lp=p/p'$, R is a major radius, s is the magnetic shear, Bp is a poloidal field, $Iaux$ is an external current at the O-point of the island with a width of δJ, and Δ' is the standard tearing stability index. The saturated island width w_{sat} is obtained by iterative calculations using the numerical equilibrium. The above equation indicates that the island width is enhanced by a weaker shear (larger Lq), steeper pressure gradient (smaller Lp) and also a local current ($Iaux$) at the O-point of the island reduces the island width.

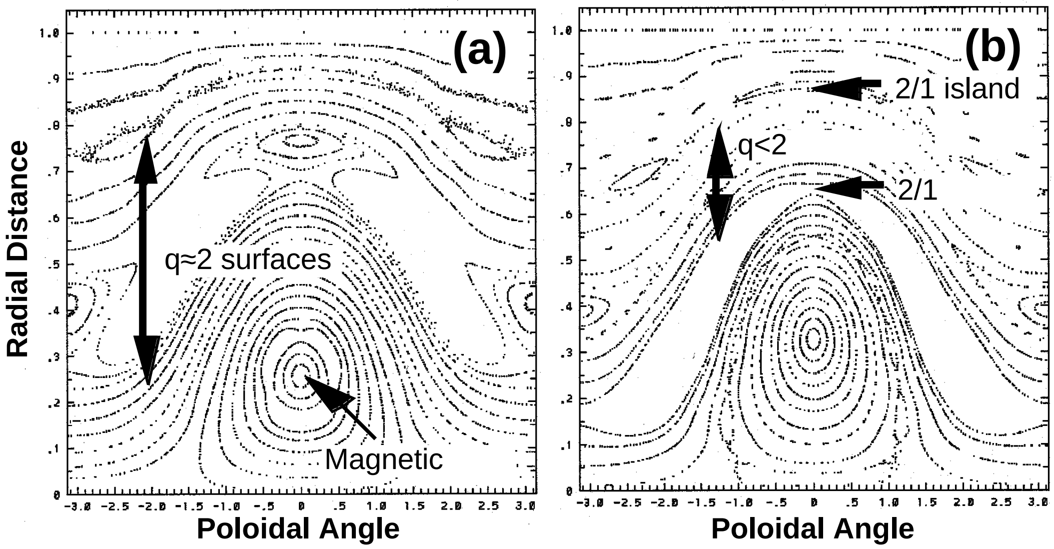


FIG. 3. Poincaré plots of negative shear magnetic field for (a) $q_{min}>2$ and (b) $q_{min}<2$ in saturation.

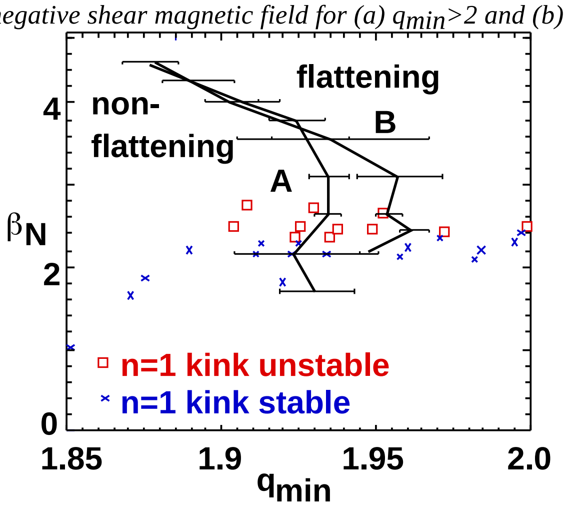


Fig.4 Comparison of the boundary of q profile flattening and no flatting regions (solid lines; A is for a 30 radial mesh, B is for a 60 radial mesh) and the boundary of the n=1 kink mode

Stability results of weak positive shear are shown by lines A in Fig.5 for no external current (*Iaux*=0). The saturated island width reaches 30% of the minor radius even for the low $ß_N$ (~1). It can also be seen in Fig.4 that a local current drive effectively stabilizes the neoclassical tearing mode. The local current of 20kA (~2% of the total current) with a width of 10% of the minor radius reduces the island width significantly, and increases the boundary from A to B. To reduce the island width, localization of the externally driven current is effective as shown in Fig.5B. Ray tracing analysis of the electron cyclotron current drive (ECCD) by the fundamental resonance of the ordinary wave with 110GHz shows localized current drive over a radial region less than 10% of the minor radius is achievable for JT-60 like configuration with $n_{e0}=1\times10^{20}[m^{-3}]$, Teo=10keV and R_0=3.4m[8]. The current drive efficiency, $\gamma=\langle ne\rangle R_0 I/P_{inp}$, is estimated as ~0.03 at the half minor radius and an external current of 20kA can be driven by about 1 MW power of EC wave.

4. KINETIC MHD STABILITY

The high frequency kinetic ballooning mode (KBM) can have adverse effects on confinement of alpha particles in the present high ß tokamak discharges and possibly in future tokamak reactors as well even though it is unlikely that the observed KBM is driven directly by the alpha particles pressure gradient. In light of the importance of KBM to plasma confinement, it is worthwhile to further our understanding of kinetic ballooning type modes in tokamaks that exist outside the MHD regime, namely, stability of such modes in the MHD second stability regime and negative shear regime wherein the ion magnetic drift resonance remains active.

The present stability analysis is based on the kinetic ballooning mode equation developed in [9]. The nature of the kinetic ballooning mode in the negative shear and the weak shear regimes is clarified through the behavior of the eigenfunction[10]. It is found to be a continuation of the MHD ballooning mode, not of the second mode with a smaller growth rate which coexists with the MHD mode. Also studied is the mode stability in the negative shear region, where the MHD ballooning mode is known to be stable. The KBM clearly persists in negative shear region. The unstable region in positive shear also broadens. The kinetic ballooning mode persists for $s < 0$ with a narrow stable window near weak shear. Complete stabilization of the instability requires large shear, s <-1 or s > 1.5.

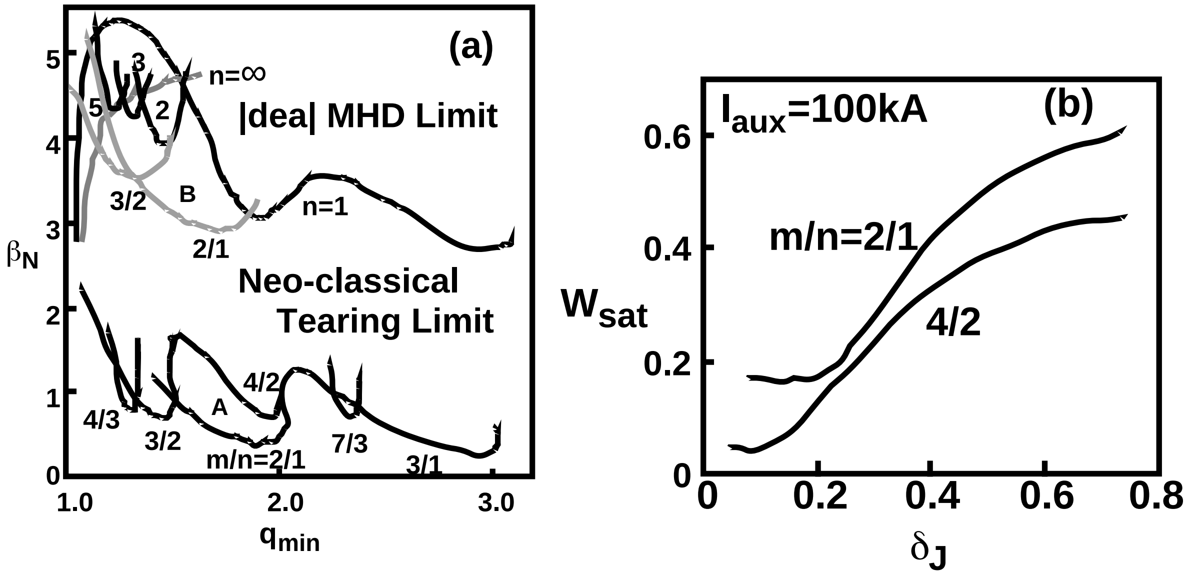


*Fig.5 (a) Beta limits against the ideal MHD mode and the neoclassical tearing mode (the limit is determined when a saturation island width is a 30% minor radius) in the weak positive shear configuration with li~1.2 and a slightly broad pressure profile: $p' \propto 0.3x(1-\psi)^{0.5}+0.7$. The line A is for Iaux=0 and the line B is for Iaux=*20kA (*Iaux/Ip*=0.02), δJ=0.1 ($\delta_J/w_{sat}(I_{aux}=0)$ ~0.2).
Fig.5 (b) Saturated island width, w_{sat}, against the width of an additional current, δ_J.

5. SUMMARY AND DISCUSSION

Comprehensive MHD stability analysis clarifies the characteristics of MHD stability and suggests means of stabilization. In the negative shear configuration, the hard beta limit due to ideal MHD stability can be improved by increasing the pressure gradient near the plasma surface and by moving the maximum pressure gradient to the negative shear region. Large negative shear (large q_O/q_{min}) makes the ideal MHD mode stable, but the resistive interchange mode becomes unstable. The double tearing mode may emerge when the qmin is just under the m=2 rational surface, but the small current modulation, reducing the shear, at the outer resonance surface makes the double tearing mode stable. In the weak shear configuration, the beta collapse due to ideal MHD stability can be improved by reducing the pressure gradient in the weak shear region. The double tearing mode can also be avoided. However, the neoclassical tearing mode reduces the beta limit below the ideal kink limit. The localized additional current ($w_{sat}/\delta J$~0.2, *Iaux/Ip*~0.02) on the O-point of the island reduces the island width significantly. It has also been shown that the KBM (kinetic ballooning mode) persists in negative shear region with a modest ion temperature gradient, although the growth rate is smaller than that in positive shear. Stabilization of the KBM requires a large shear, positive or negative. A narrow stable window appears near null shear. It expands with an increase in the pressure gradient.

In the negative shear plasma, the improvement of the low n kink is the critical issue, and finding a self-consistent equilibrium with the broad pressure and the strongly negative q-profile, i.e., high q_0/q_{min} and q_s/q_{min}, is the essential issue. More investigation of the double tearing near q_{min}=2 is necessary to obtain the equilibrium with low q_{min} and large q_O/q_{min}. In the weak shear plasma, the ideal MHD improved by large li and broad pressure profile and the stabilization of the neo-classical tearing mode is the critical issue. The present analysis were made for no wall stabilization. For higher $\beta_N > 3.5$, the wall stabilization of the steady state plasma is a critical issue, especially for the negative shear plasma.

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