Stability Analysis of Toroidicity-Induced Alfvén Eigenmodes in TFTR Deuterium-Tritium Experiments

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The toroidicity-induced Alfvén eigenmodes (TAE) are found to be stable in the Tokamak Fusion Test Reactor (TFTR) deuterium-tritium plasmas. The dominant stabilizing mechanisms are beam ion Landau damping and radiative damping. A core localized TAE mode is shown to exist near the center of the plasma at small magnetic shear and finite plasma beta, which can be destabilized by energetic alpha particles in future TFTR DT experiments. With additional instability drive from fast minority ions powered by ion cyclotron radio frequency, both the global and core localized TAE modes can be readily destabilized.

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Record fusion powers have recently been achieved in the Tokamak Fusion Test Reactor (TFTR) deuterium-tritium (DT) experiments [1]. A key question is whether the toroidicity-induced Alfvén eigenmode (TAE) [2] can be destabilized by the energetic alpha particles [3] in the TFTR DT experiments. This could have serious implications for fusion reactors, since the TAE instability can induce large fusion alpha particle loss, which could lead to a loss of alpha heating or damage to the first wall. Previous experiments have shown that TAE modes can be strongly destabilized by energetic D ions in neutral-beam-injection- (NBI-) heated plasmas [4,5] and by fast hydrogen minority tail ions in ion cyclotron radio frequency (ICRF) heated plasmas [6].

A search for alpha-driven TAE modes was made during the first phase of TFTR DT operation, when up to 6.4 MW of fusion power was produced in supershot discharges at $B = 5$ T and $I = 2$ MA (e.g., shot No. 73268). No significant TAE fluctuations were seen either in the edge magnetic loops or in the reflectometer measurements of internal density fluctuations [7].

The stability of TAE modes in the first phase of TFTR DT experiments is analyzed using the global kinetic, magnetohydrodynamic (MHD) stability code NOVA-K [8,9]. Our numerical results show that the TAE modes are stable in typical TFTR NBI-heated DT plasmas, which is consistent with the experimental observations. Similar results have also been obtained in Ref. [10] using a gyrofluid model. However, in a more recent TFTR DT discharge with 7.5 MW of fusion power (shot No. 76770), our calculations indicate that a core localized TAE mode exists and is nearly unstable due to large alpha particle drive.

There are two types of TAE modes. For the first type, the radial mode structure is global and extended between the half radius and plasma edge, as shown in Fig. 1(a), which plots the radial displacement ξ_ψ of a $n = 3$ TAE as a function of minor radius for several poloidal harmonics. The corresponding $n = 3$ shear Alfvén continuum is shown in Fig. 1(b). Most of the TAE modes computed for TFTR supershot plasmas are of this type.

Here we report first results of a second type of mode, called core localized TAE modes, at small magnetic shear and finite plasma beta. Figure 2(a) shows such a core localized mode in a TFTR DT plasma (shot No. 76770). The corresponding $n = 5$ shear Alfvén continuum spectrum is shown in Fig. 2(b). The mode is localized at the first continuum gap near the $r/a = 0.2$ surface and has only two appreciable poloidal harmonics with comparable amplitude. The mode frequency is located just above the lower bound of the corresponding

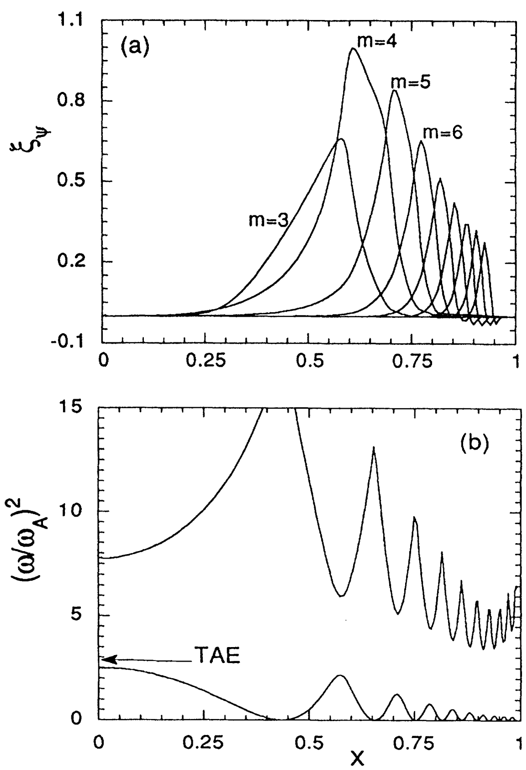

FIG. 1. (a) The radial displacement ξ_ψ of a $n = 3$ TAE mode as a function of plasma minor radius. (b) The $n = 5$ shear Alfvén continuum spectrum $(\omega/\omega_A)^2$, where $\omega_A = v_A(0)/q_a R$.

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continuum gap. This core localized TAE mode can exist at finite beta due to finite aspect ratio effects as shown analytically in Ref. [11]. Recently, it has been shown that there is another core localized TAE induced by the finite aspect ratio effects [12]. The eigenfrequency of this mode is located near the upper bound of the continuum gap. It turns out that in most high-power TFTR DT discharges, such as the 6.2 MW shot (No. 73268), the plasma beta is still too large for the core localized TAE mode to exist, and only the extended TAE can exist.

Now we turn to stability calculations of TAE modes for both types using the kinetic MHD stability code NOVA-K. To destabilize TAE, the instability drive associated with the alpha particle pressure gradient must overcome damping effects due to all particle species. The NOVA-K code calculates perturbatively the alpha particle drive, the Landau damping of thermal species and beam ions, and the collisional damping of trapped electrons. The nonperturbative radiative damping [13] is also included using a boundary layer method [14]. The effects of finite orbit excursion from the flux surface due to magnetic curvature drift are included for both alpha particles and beam ions. All calculations are performed with realistic equilibria. The continuum damping [15] is expected to be small for most cases considered and is neglected. For example, there are usually no continuum resonances for global TAE modes, such as shown in Fig. 1. For the core localized TAE modes, the mode frequencies often intersect with the continua near the plasma edge, such as shown in Fig. 2(b). Nonetheless, the continuum damping is presumed to be small due to the localized mode structure.

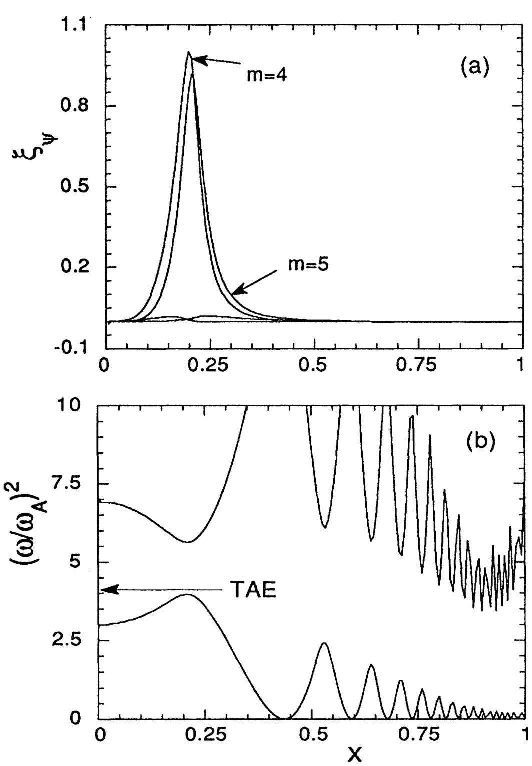

FIG. 2. (a) The radial displacement ξ_ψ of a $n = 5$ TAE mode as a function of plasma minor radius. (b) The $n = 5$ shear Alfvén continuum spectrum $(\omega/\omega_A)^2$.

Our results indicate that the global TAE modes are stable in the TFTR NBI-heated DT plasmas. This is consistent with the experimental observations. Figure 3 shows the critical central alpha beta for TAE instability versus toroidal mode number obtained for a DT discharge (shot No. 73268). The alpha beta value calculated by TRANSP [16] is also marked on the figure. The experimental value is about a factor of $\frac{1}{4}$ of the calculated $\beta_\alpha(0)$ threshold. Analysis of other NBI-heated DT discharges yields similar results. The parameters of shot No. 73268 are the major radius $R = 252$ cm, the minor radius $a = 87$ cm, the toroidal magnetic field $B = 5$ T, the plasma current $I_p = 2.0$ MA, the central plasma beta $\beta(0) = 4.6\%$, the central alpha beta $\beta_\alpha(0) = 0.18\%$, the central electron density $n_e(0) = 7.6 \times 10^{13}$ cm^{-3}, the ion temperature $T_i(0) = 28$ keV, the electron temperature $T_e(0) = 10.5$ keV, and the safety factor $q(0) = 0.84$ at the center and $q(a) = 5.1$ at the edge. The plasma pressure profile and the q profile are obtained with the TRANSP code [16].

We find that the beam ion Landau damping and the radiative damping are the two most important stabilizing mechanisms. For example, the drive and damping increments for the $n = 5$ mode considered in Fig. 3 are as follows: the alpha drive $\gamma_\alpha/\omega = 0.26\%$, the electron damping rate $\gamma_e/\omega = -0.15\%$, the beam ion Landau damping rate $\gamma_{\text{beam}}/\omega = -0.38\%$, and the radiative damping $\gamma_r/\omega = -0.64\%$. The thermal ion Landau damping and the electron collisional damping are both negligible. These results are typical for global TAE modes. Physically, the thermal ion Landau damping is small because of low ion temperatures near the edge.

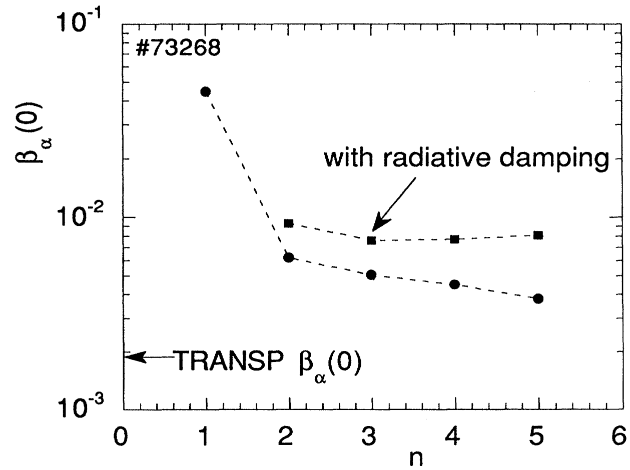

FIG. 3. The critical central alpha beta value as a function of toroidal mode number for the TFTR DT discharge No. 73268.

Likewise, the electron collisional damping is small due to low electron beta values. On the other hand, the electron Landau damping is appreciable as a result of effective resonance at lower electron temperature. The beam ion Landau damping is large because large beam ion velocity allows sideband resonance at $v_{\parallel} \approx v_A/3$. Furthermore, our numerical results show that the beam ion damping is enhanced greatly by the effects of finite orbit width due to magnetic drift, typically by a factor of 3 to 10. This large enhancement comes from additional sideband resonances induced by drift orbit [17]. Finally, the radiative damping is large due to relatively high mode number.

We now turn to the stability of the core localized TAE modes near the *lower* bound of the continuum gap. For the TFTR discharge (shot No. 76770 at 4.3 sec) considered above, we find that the $n = 5$ core localized mode is weakly unstable due to large alpha particle drive, in the absence of radiative damping. However, the mode becomes marginally stable when the radiative damping is included. The ratio of drive and total damping is about 0.7. The $n = 6$ mode has also been calculated and is found to be more stable. The drive and damping increments for the $n = 5$ mode are given by $\gamma_\alpha/\omega = 1.9\%$, the thermal ion Landau damping $\gamma_i/\omega = -0.63\%$, the beam ion Landau damping $\gamma_{\text{beam}}/\omega = -1.19\%$, and the radiative damping $\gamma_r/\omega = -0.9\%$. The beam ion Landau damping and the radiative damping are still the two dominant stabilizing mechanisms. These results are obtained with the following parameters: $R = 252$ cm, $a = 87$ cm, $B = 5$ T, $I_p = 2.5$ MA, $\beta(0) = 3.1\%$, $\beta_\alpha(0) = 0.24\%$, $n_e(0) = 7.5 \times 10^{13}$ cm^{-3}, $T_i(0) = 22$ keV, $T_e(0) = 11$ keV, and the safety factor $q(0) = 0.88$ and $q(a) = 4.1$. This central ion temperature (at 4.3 sec) is considerably lower than the peak value which occurs early in the discharge.

The stability of the core localized TAE mode near the *upper* bound of the continuum gap has also been calculated. The $n = 5$ mode near the upper bound is found to be more stable due to smaller alpha drive as compared to that of the mode near the *lower* bound. The alpha drive for the *upper* mode is weak because the finite orbit width effect of alpha particles is stabilizing. This stabilizing effect is much stronger for the *upper* TAE mode, which has a narrower radial mode width as compared to the *lower* mode.

It is instructive to compare the relative size of drive and dampings of the $n = 5$ core localized mode with that of the $n = 5$ extended TAE in Fig. 3. We observe that the alpha particle drive for the core localized mode is much larger. This is because the mode peaks near the center of plasma where the alpha particle pressure gradient is the largest. The beam ion Landau damping is also larger due to higher beam ion beta at the mode peak. The thermal ion Landau damping is now appreciable because of higher ion temperature.

The beam ion Landau damping is sensitive to the beam injection energy. For typical TFTR DT parameters, $v_{\text{D}}/v_A(0) \approx 0.37$ and $v_{\text{T}}/v_A(0) \approx 0.30$, where v_{D} and v_{T} are the deuterium beam injection speed and the tritium beam injection speed, respectively. Thus the deuterium ion damping is usually larger than the tritium ion damping with equal DT concentration. For the $n = 5$ core localized TAE considered in this paper, the deuterium damping is much larger than the tritium beam damping. We have numerically studied the effect of injection energy E_b on the beam damping. We find that the deuterium beam damping is maximized at $v_{\text{D}}/v_A(0) = 0.33$ (at $E_b = 80$ keV). The damping falls appreciably when the value of $v_{\text{D}}/v_A(0)$ decreases below 0.33. At $v_{\text{D}}/v_A(0) = 0.29$ (at $E_b = 60$ keV), the damping is reduced by a factor of 22 from the maximum. The results for the tritium beam damping are similar. Physically, the beam damping is sensitive to injection velocity near $v_A/3$, because the main contribution to the damping comes from the $v_{\parallel} = v_A/3$ resonance. From this analysis, it is clear that the beam damping is only important when $v_{\text{D}}/v_A(0) > 0.3$. This condition can be applied to JET, JT-60U, or ITER, where neutral beam heating could be used to stabilize TAE modes.

Up until now, we have only considered instability drive from alpha particles in TFTR DT experiments without ICRH. However, with ICRH additional drive could come from fast minority tail ions with their energy on the order of MeV. This additional drive can potentially be very important since ICRH power ($\sim$5 MW) is typically much larger than the alpha particle power ($<$2 MW). For typical parameters, we find that the ICRH drive is much larger than the alpha drive for global TAE modes, but for core localized TAE modes, the ICRH drive is comparable to the alpha drive. For example, the calculated ICRH drive for the $n = 5$ global TAE mode in the discharge (No. 73268) would be 7 times larger than the alpha drive if 5 MW of ICRH were present. On the other hand, for the $n = 5$ core localized TAE in the discharge (No. 76770), the ICRH drive would be 25% smaller than the alpha drive. These results are obtained by assuming the following parameters for hydrogen minority ICRF heating: $\beta_h(0) = 0.7\%$, $T_h(0) = 0.5$ MeV, and the pressure profile $P_h \propto (1 - \sqrt{\Psi}/0.5)^2$ for $\sqrt{\Psi} < 0.5$ and $P_h = 0$ for $\sqrt{\Psi} > 0.5$. We see that the alpha particles with a smaller power ($\sim$1.5 MW) can actually provide a similar drive for core localized TAE mode as compared with minority ions powered by ICRH ($\sim$5 MW). This is because the particle distribution of minority ions is quite different from that of isotropic alpha population. It is known that the finite drift orbit width effects can reduce the fast particle drive. Since minority ions are mostly trapped particles, this stabilizing orbit effect is much stronger, as shown by our NOVA-K results. From this analysis, we conclude that TAE modes can be readily destabilized in TFTR DT experiments with ICRH.

So far, there is no direct experimental evidence that the core localized TAE mode exists in the TFTR DT plasmas. However, in the TFTR ICRF heated *deuterium* plasmas, there are indications from the reflectometer data that the core localized TAE modes do exist in these plasmas. Figure 4 shows the fluctuation spectrum in the range of frequencies of TAE modes in an ICRF heated TFTR deuterium plasma with both microwave reflectometry and Mirnov measurements [18]. At $r/a \sim 0.4$, the reflectometer observes the same spectrum of fluctuations as measured by Mirnov coils. On the contrary, near the center of the plasma where $q < 1$, the reflectometer measures fluctuations in the TAE range of frequencies which are not observed on the Mirnov signals. This suggests the existence of core localized TAE modes. The results of NOVA-K code have indeed confirmed the existence of several core localized modes in this particular discharge. The calculated mode frequencies and stability threshold agree with the experimental observations.

In future TFTR DT experiments, it might be useful to actively destabilize TAE modes in order to study their instability property and associated transport. One way is by reducing the beam ion Landau damping with a lower beam injection energy. Another way to excite TAE is to increase the alpha particle drive. This can be done by modifying the pressure profile such that the core localized TAE mode can exist. Additional TAE instability driven such as ICRH fast tail ion drive can greatly enhance the possibility of TAE instability. In the International Thermonuclear Engineering Reactor (ITER), our initial calculations indicate that high-n TAE modes are unstable.

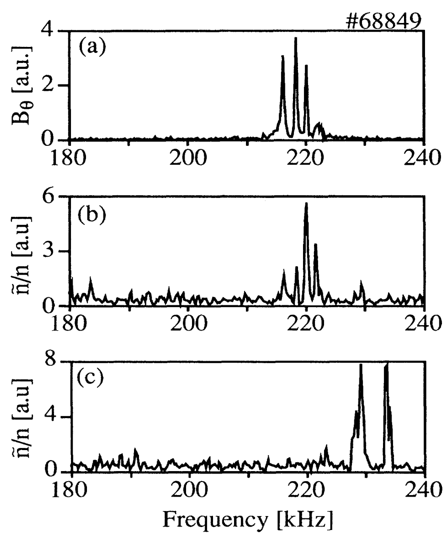

FIG. 4. Spectrum of observed fluctuations in the TAE range of frequencies during ICRF heating in TFTR plasmas. (a) Edge magnetic fluctuations, (b) reflectometer measurements of density fluctuations at $r/a \sim 0.4$, and (c) reflectometer measurements of density fluctuations at $r/a \sim 0.1$.

In conclusion, TAE modes are found to be stable in the TFTR NBI-heated DT plasmas without ICRH. The main stabilizing mechanisms are beam ion Landau damping and the radiative damping. A core localized TAE mode is shown to exist at small magnetic shear and finite plasma beta, and can be destabilized in future TFTR DT experiments due to large alpha particle drive. Additional instability drive from fast minority ions powered by ICRH can excite both global TAE and core localized TAE modes.

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