First Evidence of Collective Alpha Particle Effect on Toroidal Alfvén Eigenmodes in the TFTR D-T Experiment

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The alpha particle effect on the excitation of toroidal Alfvén eigenmodes (TAE) was investigated in deuterium-titrium (D-T) plasmas in the Tokamak Fusion Test Reactor. rf power was used to position the plasma near the instability threshold, and the alpha particle effect was inferred from the reduction of rf power threshold for TAE instability in D-T plasmas. Initial calculations indicate that the alpha particles contribute 10%–30% of the total drive in a D-T plasma with 3 MW of peak fusion power.

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Collective phenomena associated with the energetic alpha particles in a deuterium-tritium (D-T) fusion reactor have been anticipated in the past two decades. Alfvén type instabilities [1] are expected to occur when the pressure gradient of the fast alpha particles exceeds the instability threshold. It is important to avoid these instabilities in a fusion reactor because they can eject the alpha particles before they thermalize in the plasma, thereby causing localized heating and damage of the first wall. Simulation experiments, performed recently with the energetic ions produced by neutral beam injection [2–4] and ion cyclotron range of frequency (ICRF) heating [5,6], show that toroidal Alfvén eigenmodes [7] (TAE's) can indeed be excited. These modes have a ballooning mode structure; i.e., their amplitude peaks at the large-major-radius side of the flux surface [5]. The D-T plasmas in the Tokamak Fusion Test Reactor (TFTR) [8] provide for the first time an environment suitable for the investigation of the interaction between the alpha particles and these instabilities in reactor-relevant parameters. Although edge Alfvén modes have been observed in D-T plasmas in the TFTR, there is no evidence of TAE instabilities up to 10.7 MW of fusion power. This is because the alpha particle pressure gradient is still below the instability threshold. In this paper, we present the results of an experiment using the incremental drive technique to study the interaction between the fast alpha particles and the TAE modes. To the best of our knowledge, this is the first experiment to estimate the alpha particle contribution to the TAE instability drive in a tokamak.

ICRF heating of the minority hydrogen ions produces energetic protons which can assist the excitation of the TAE instability. Let γ_{H} and γ_α represent the growth rate of the instability due to the fast protons and alpha particles, respectively. The total growth rate driven by the protons and the alpha particles is the sum of the two, i.e., $\gamma = \gamma_{\mathrm{H}} + \gamma_\alpha$. By increasing the ICRF power, we can increase γ_{H} so that γ exceeds the damping rate and the mode becomes unstable. Let P_{DT} and P_{DD} denote the rf power threshold for TAE instabilities in D-T and D-D plasmas, respectively, and γ_d is the damping rate. At the instability threshold,

$$\gamma_{\mathrm{H}}(P_{\mathrm{DT}}) + \gamma_\alpha - \gamma_d(P_{\mathrm{DT}}) = 0 \qquad \text{in D-T plasmas},$$

$$\gamma_{\mathrm{H}}(P_{\mathrm{DD}}) - \gamma_d(P_{\mathrm{DD}}) = 0 \qquad \text{in D-D plasmas}.$$

If D-T and D-D plasmas have similar parameters and the same damping rate for TAE modes, then

$$\gamma_\alpha = \gamma_{\mathrm{H}}(P_{\mathrm{DD}}) - \gamma_{\mathrm{H}}(P_{\mathrm{DT}}). \tag{1}$$

In the regime where γ_{H} increases with rf power, the alpha particle effect would be reflected in a reduction of the rf power threshold in D-T plasmas. This was observed in the TFTR experiment. Here we present these data as the first experimental evidence of collective alpha particle effect in a D-T plasma.

The experiment was performed in TFTR with the following plasma parameters: $I_p = 1.8$ MA, $R = 2.62$ m, $a = 0.96$ m, $n_e(0) \sim 5 \times 10^{13}$ cm^{-3}, $T_e(0) \sim 9.5$ keV, $T_i(0) \sim 25$ keV, toroidal magnetic field $B_T = 4.23$ T on the magnetic axis at $R = 2.83$ m, neutral beam power $P_b \sim 20$ MW, rf power $P_{\mathrm{rf}} \leq 5.5$ MW, and the peak D-T fusion power is about 3 MW. The wave forms for P_b and P_{rf} and the neutron rate are shown in Fig. 1. In our experiment, the TAE modes appear 100–200 ms after the rf power is turned on. This is the time required to heat the H minority ions to energies high enough for TAE excitation. Fig. 2 compares the frequency spectra of the Mirnov coil signals at various rf power levels in D-T and D-D plasmas. It is apparent that at the same rf power, the TAE amplitude is, with no exception, always higher in D-T plasmas. The first three peaks in Fig. 2(a) are TAE modes with toroidal mode number $n = 6$, 7, and 8. The $n = 6$ mode has the lowest threshold; it appears first when we raise the rf power. Since the frequency spectrum changes with rf power, it is difficult to make a quantitative comparison on the TAE amplitude. More peaks appear in

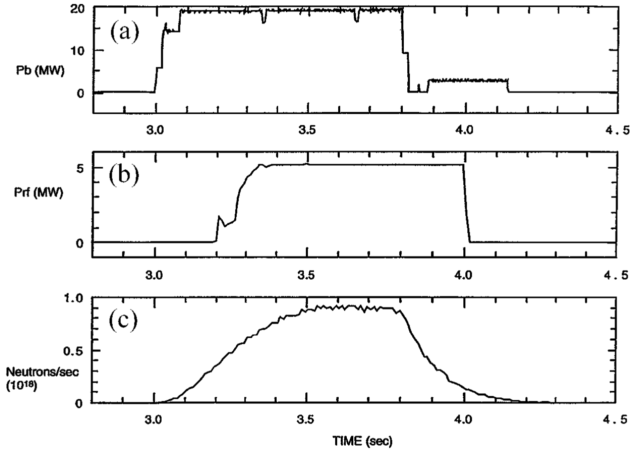

FIG. 1. Wave forms for (a) neutral beam power, (b) ICRF power, and (c) fusion neutron flux.

the spectrum at higher rf power. We integrate over these peaks by choosing the instrumental frequency bandwidth broader than the frequency separation between the peaks, and we use this signal as a measure of the TAE amplitude. Its variation with rf power is plotted on Fig. 2(e). The rf power in these shots varies from 4.0 to 5.5 MW which is only a very small change compared with 25 MW of total heating power. The measured bulk plasma parameters are quite similar in these shots. The main difference is in the central ion temperature which is 13% higher in D-T plasmas. However, this has negligible effect on the TAE damping rate because ion Landau damping is mainly due to the energetic beam ions. The rf power threshold for the TAE instability in the D-T plasma is just below 4 MW; it is about 20% lower than in similar D-D plasmas (about 5 MW). When $4.0 < P_{\mathrm{rf}} < 5.0$ MW, TAE modes appear only in D-T plasmas, suggesting the possibility of alpha particle effect on this instability.

The density oscillations in the plasma interior associated with the TAE modes can be detected by a three-channel microwave reflectometer [9] tuned to $R = 295$, 310, and 320 cm which correspond to $r/a = 0.16$, 0.35, and 0.48. The frequency spectra of the reflectometer data are shown in Fig. 3. The maximum signal appears in the middle channel tuned to $R = 310$ cm. The peaks at 228.7, 231.4, and 234.7 kHz are also observed in the Mirnov coil signal for this plasma. Phase measurements by the toroidal Mirnov coil array indicate that the dominant mode has a toroidal mode number of $n = 6$. The density oscillation is roughly estimated to be $\delta n/n \sim 10^{-4}$. The fast ion loss rate at a probe 45° below the outer midplane increased by about a factor of

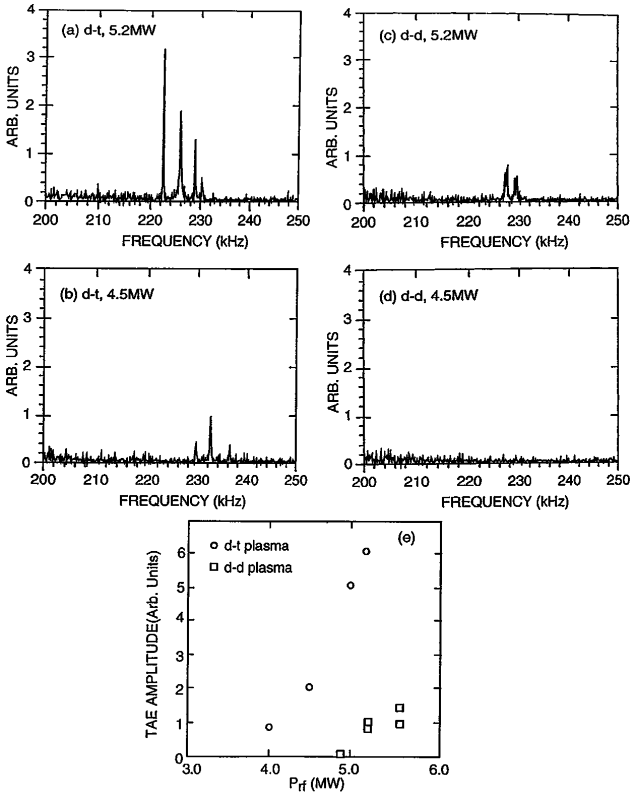

FIG. 2. Variation of Mirnov coil signal under different conditions: (a) D-T plasma with 5.2 MW of rf power, (b) D-T plasma with 4.5 MW of rf power, (c) D-D plasma with 5.2 MW of rf power, (d) D-D plasma with 4.5 MW of rf power, and (e) TAE mode amplitude at various rf power.

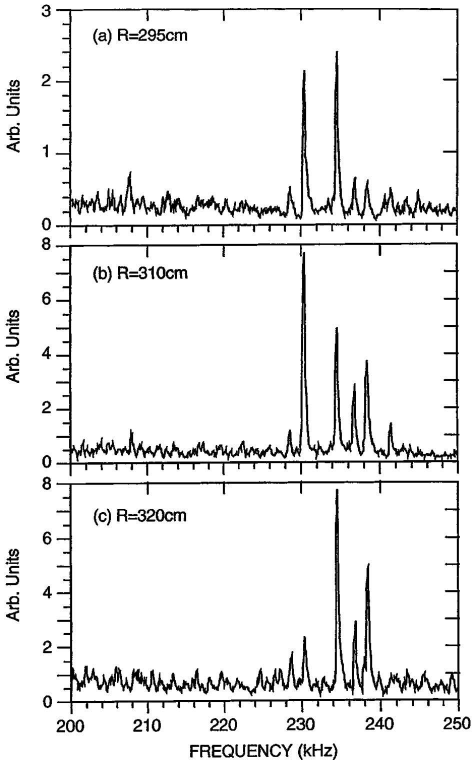

FIG. 3. Power spectrum of the reflectometer signal from various locations: (a) $R = 295$ cm, (b) $R = 310$ cm, and (c) $R = 320$ cm. It is a D-T plasma with 5.4 MW rf power. Although the sensitivity of these three channels are roughly the same, they are not absolutely calibrated.

2 during the TAE activity. This probe [10], under these conditions, detects only H minority tail ion loss.

In the data analysis, we first assess γ_H by calculating the distribution of the rf power absorption among various charged species in the plasma. The rf power is absorbed primarily by the minority hydrogen ions with a fundamental cyclotron resonance passing through the plasma core, and by deuterium ions at the second harmonic. Analysis carried out with the FPP Fokker-Planck code [11] and the SNAP [12] and TRANSP [13] transport codes indicates that 50%–70% of the rf power is absorbed by the hydrogen ions with the accuracy of the calculation related to uncertainty in the minority density and deuterium and hydrogen effective temperatures. The calculation of the minority ion temperature T_{eff} is influenced by the small-orbit assumption made in the calculation but not strictly valid in our experiment. We rely on the active charge-exchange [14] measurement to determine T_{eff} in the plasma core. For this measurement, a lithium pellet was injected into D-D and D-T plasmas during rf heating but 200 ms after the turn-off of neutral beams so that the pellet could reach the plasma core. The data depicted in Fig. 4 show that for the same rf power, T_{eff} is similar in both plasmas. We conclude that at a given rf power level, γ_H is approximately the same in both D-D and D-T plasmas.

The next step is to evaluate the TAE damping rates. The most likely difference between the D-T and the D-D plasmas would come from the ion Landau damping [15] by the fast beam ions with $v_\parallel \approx V_A/3$. There was a conjecture that ion Landau damping by the deuterium beam ions is dominant in these plasmas. Replacement of tritium beams with deuterium beams would result in more deuterium beam ions in the plasma, thereby causing stronger ion Landau damping and a higher instability threshold. In order to experimentally evaluate the significance of the ion Landau damping effect due to the difference in the beam ion species, we varied the deuterium beam power and investigated its effect on the TAE instability. Shot 83044 with 5 tritium beam sources and 2 deuterium beam sources has the same fusion reaction rate as shot 83046 with 4 tritium beam sources and 4 deuterium beam sources. Since they also have the same rf power, γ_α and γ_H should be very similar for the two discharges. If ion Landau damping by the deuterium beam ions is the dominant damping mechanism, changing from 2 deuterium beam sources to 4 deuterium beam sources would double the deuterium beam ion density as well as the damping rate and stabilize the TAE modes. This obviously did not happen as shown in Fig. 5. The saturated TAE amplitudes in these two shots are very similar. This result indicates that ion Landau damping by deuterium beam ions is not the dominant damping mechanism in the D-T plasma in this experiment.

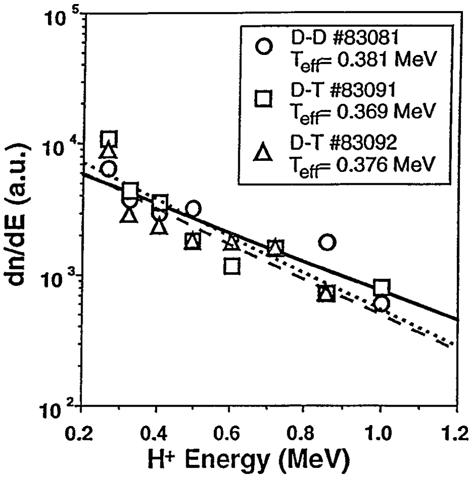

FIG. 4. Energy spectrum of the hydrogen minority ions heated by 5.2 MW of ICRF power in D-D and D-T plasmas.

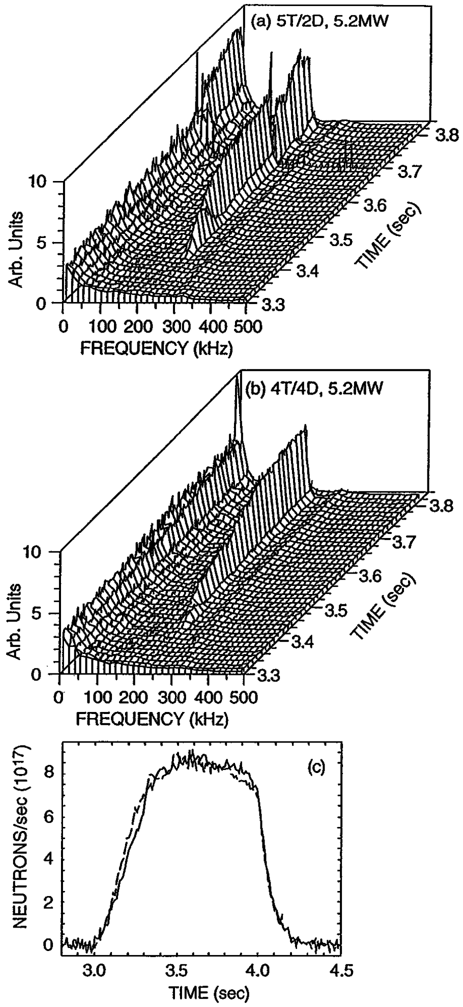

FIG. 5. Comparison of two different D-T plasmas with 5.2 MW of rf power: (a) TAE amplitude in a D-T plasma with 5 tritium and 2 deuterium beam sources. There was a sawtooth crash near 3.69 sec which caused a sudden change in the TAE amplitude. (b) TAE amplitude in a D-T plasma with 4 tritium and 4 deuterium beam sources. (c) Overlay of the fusion neutron flux from the above two D-T plasmas.

The ion Landau damping rate can be estimated from local theory as follows:

$$\gamma_{\mathrm{ILD}}/\omega \approx -\sqrt{\pi}\, q^2 \beta_i (1 + x^2) x^3 \exp(-x^2)\,,$$

$$x \equiv V_A/3v_i\,, \qquad (2)$$

where v_i is the thermal velocity of the fast ions assumed to have a Maxwellian distribution function. In D-T shots, tritium is introduced into the plasma through neutral beam injection at energies similar to the deuterium neutral beams in D-D shots. Since tritons are heavier than deuterions, they are injected at a slower velocity and give a smaller ion Landau damping rate per ion. However, TRANSP analysis shows that the pressure from the deuterium beam ions is lower than that for the tritium beams primarily because of the lighter deuteron mass and the shorter slowing down time due to electron drag. Application of Eq. (2) to D-T shot 76181 with plasma parameters at $R = 310$ cm obtained from the TRANSP code yields $\gamma_{\mathrm{ILD}} = -1.5 \times 10^4$ rad/sec. For the D-D comparison shot 76179, we obtain $\gamma_{\mathrm{ILD}} = -1.6 \times 10^4$ rad/sec which is very close to that of the D-T shot.

The preceding local analysis indicates that the reduced rf power threshold for TAE instabilities in D-T plasmas is probably due to the alpha particles produced from D-T fusion reaction. Further studies based on global analysis with the NOVA-K code [16] were also performed. The calculated mode frequency for the $n = 6$ mode is 224 kHz, which is within 3% of the measured value. This is a global mode; the core localized mode [17] is found to be stable in our plasma. It was found that at 5.2 MW of rf power, the $n = 6$ mode has $\gamma_d \sim 2.9 \times 10^{-2}\omega$, $\gamma_\alpha \sim 3 \times 10^{-3}\omega$, and $\gamma_{\mathrm{H}} \sim 2.3 \times 10^{-2}\omega$, i.e., $\gamma_\alpha/\gamma_d \sim 10\%$. This can be compared with the result deduced from the reduction in rf power threshold for the TAE instabilities in deuterium plasmas. When TAE modes become unstable, they grow and saturate at an amplitude which increases with the initial growth rate. For example, if wave-particle trapping [18] is the saturation mechanism, the final amplitude is proportional to the square of the initial growth rate. Therefore, the data in Fig. 2(e) can be used to estimate the alpha particle contribution to the instability drive. At 4.0 MW of rf power. the TAE mode amplitude in D-T plasmas is approximately a factor of 7 lower than that at 5.2 MW of rf power at which the incremental drive $\Delta\gamma_{\mathrm{H}} \sim 10^{-2}\omega$. The TAE amplitude in deuterium plasmas at 5.2 MW of rf power is also approximately a factor of 7 lower than that in D-T plasmas at the same rf power, indicating that the alpha particle contribution is about $10^{-2}\omega$. This number is 3 times higher than the NOVA-K result, but is within the accuracy of these estimates. The major uncertainty is in the distribution function for the hydrogen minority ions which determines γ_{H}. When there is 3 MW of fusion power in the D-T plasma, 0.6 MW is in the alpha particles. This is consistent with the 1 MW difference in the rf power threshold with 70% absorption by the H minority ions.

In summary, we have observed the first evidence of collective alpha particle effect on TAE modes in D-T plasmas in TFTR. At 3 MW of peak fusion power, the alpha particle drive is approximately 10%–30% of the damping rate. This value has large uncertainty because the driving and damping rates are sensitive to the plasma profiles calculated from modeling codes whose accuracy is difficult to quantify.

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