Alpha-Particle-Driven Toroidal Alfvén Eigenmodes in the Tokamak Fusion Test Reactor

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Alpha-particle-driven toroidal Alfvén eigenmodes (TAEs) have been observed for the first time in deuterium-tritium (D-T) plasmas on the tokamak fusion test reactor (TFTR). These modes are observed 100–200 ms following the end of neutral beam injection in plasmas with reduced central magnetic shear and elevated central safety factor $[q(0) > 1]$. Mode activity is localized to the central region of the discharge $(r/a < 0.5)$ with magnetic fluctuation level $\tilde{B}_\perp/B_\parallel \sim 10^{-5}$ and toroidal mode numbers in the range $n = 2-4$, consistent with theoretical calculations of α-TAE stability in TFTR. [S0031-9007(97)02857-3]

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Deuterium-tritium (D-T) plasma operation on the tokamak fusion test reactor (TFTR) provides the first opportunity to investigate the interaction of fusion alpha particles with plasma waves under reactor relevant conditions. Such investigations are crucial for assessing the impact of plasma instabilities on the confinement of energetic alpha particles, which are required to sustain ignition in a D-T reactor. One candidate instability with the potential for affecting alpha particle confinement in tokamaks is the toroidal Alfvén eigenmode (TAE) [1]. This Letter describes the first observation of purely alpha-particle-driven TAEs in TFTR with central β_α as low as 0.02% ($\beta_\alpha \equiv$ alpha particle pressure/magnetic pressure), well below that expected in the International Thermonuclear Experimental Reactor (ITER) [central $\beta_\alpha \sim (0.5-1)\%$].

TAEs are discrete frequency modes occurring inside toroidicity induced gaps in the shear Alfvén spectrum which can be destabilized by the pressure gradient of energetic ions. These modes can potentially cause internal redistribution and enhanced loss of energetic alpha particles in a D-T reactor due to their extended radial structure, relatively low instability threshold, and resonant interaction with 3.5 MeV alpha particles near the Alfvén velocity [2,3]. The characteristics of TAEs and associated fast ion losses have been studied in experiments utilizing circulating neutral beam ions ($E_b \leq 100$ keV) [4–6], deeply trapped minority ions in the MeV range of energy [7–9], nonlinear beat wave excitation using fast magnetosonic waves [10], and external excitation using saddle coils [11]. Until recently alpha-driven TAEs had not been observed in TFTR, even in the highest fusion power D-T "supershot" plasmas ($P_{\rm fus} \approx 10.7$ MW) with $\beta_\alpha \approx 0.3\%$ in the core of the discharge [12]. These results were consistent with theoretical calculations of alpha-driven TAE stability in TFTR, after taking into account beam ion Landau damping and radiative damping due to coupling to the kinetic Alfvén wave (KAW) [13]. However, a better comparison with theory requires the actual observation of purely alpha particle driven TAEs in D-T plasmas, as described in this Letter. The present experiment was motivated by recent theoretical calculations for low-n modes $(n < 6)$ in TFTR indicating a significant reduction in the central β_α required for destabilizing TAEs under conditions of low beam ion Landau damping, reduced central magnetic shear, and elevated central safety factor [13–17].

Figure 1 shows external magnetic measurements of $n = 3$ TAEs observed following the termination of D-T neutral beam injection in two types of TFTR discharges characterized by reduced central magnetic shear and $q(0) > 1$. The q profile and β_α are obtained from motional Stark effect measurements [18] and transport code (TRANSP) kinetic analysis, respectively [19,20]. TRANSP calculates the alpha distribution from the measured neutron rate and profile, electron and ion densities, and temperatures, using a Monte Carlo code with full gyroradius effects and collisional slowing down on the thermal species. At the time of peak TAE amplitude, the two discharges in Fig. 1 are characterized by $q(0) \approx 2.1$ (1.1), $\beta_\alpha(0) \approx 0.02\%$ (0.07%), and magnetic shear $s = rq'/q \approx 0.2$ (0.4) at $r/a \approx 0.3$. We denote these two discharges as high and low $q(0)$ plasmas. In contrast, TAE stable supershot plasmas with similar current, toroidal field, and beam power typically have $\beta_\alpha(0) > 0.1\%$ with $q(0) < 1$ and higher central magnetic shear $(s > 0.5)$ at $r/a = 0.3$.

The modes shown in Fig. 1 have not been observed in deuterium discharges with similar density, temperature,

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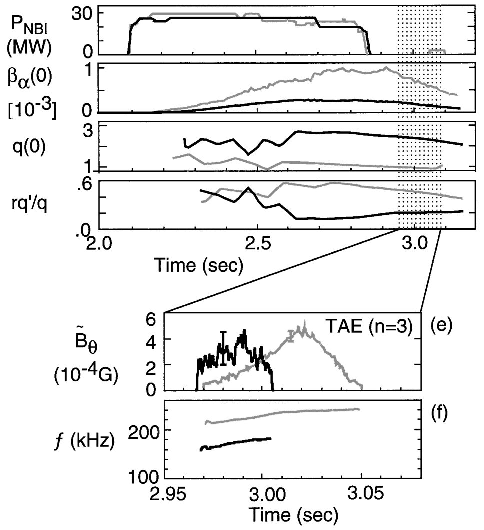

FIG. 1. Evolution of (a) neutral beam power, (b) central β_α (0), (c) central safety factor, (d) magnetic shear at $r/a \approx 0.3$, (e) external magnetic fluctuation amplitude, and (f) measured mode frequency for high and low $q(0)$ plasmas [indicated by black (gray) lines] corresponding to the following plasma parameters at the time of peak mode amplitude: $R =$ 260 cm (252 cm), $I_p = 1.6$ MA (2.0 MA), $B_T = 5.3(5.1)$ T, $n_c(0) = 3.3(4.0) \times 10^{13}$ cm^{-3}, $T_i(0) = 11(15)$ keV, $T_e(0) =$ 5.4(6.0) keV.

and q profiles, and have only been observed above a threshold fusion power in D-T plasmas with $q(0) > 1$. The peak fluctuation level of $\approx$0.5 mG in Fig. 1(e) corresponds to $\tilde{B}/B \approx 10^{-8}$ at the plasma edge. The high $q(0)$ case with weak shear ($s < 0.2$ for $r/a < 0.3$) has a similar amplitude TAE with $\approx\frac{1}{3}\beta_\alpha$ of the low $q(0)$ discharge. These modes propagate toroidally in the direction of the ion diamagnetic drift of energetic alpha particles, as expected for α-TAEs in TFTR. The measured frequency [$f \approx 160-180$ kHz at high $q(0)$ and $f \approx 220-240$ kHz at low $q(0)$] are within 15% of the calculated TAE frequency ($f_{\mathrm{TAE}} = V_A/4\pi qR$) at $r/a \approx 0.3$. The external magnetic fluctuations also feature weaker $n = 2$ and $n =$ 4 modes of similar frequency to the $n = 3$ mode in the low $q(0)$ plasma (Fig. 2). Also shown is the evolution of the $n = 3$ mode frequency, which matches closely the calculated trend in the TAE frequency ($f_{\mathrm{TAE}} \approx V_A/4\pi qR$) at $r/a = 0.3$. The contribution of plasma toroidal rotation to the mode frequency is negligible for low-n modes 100 ms after the end of beam injection.

Conditions just after the end of neutral beam injection are predicted to be optimal for excitation of alpha-driven TAEs in the core of TFTR [13,14]. The modes in Fig. 2 are observed after the slowing down time of neutral beam ions ($\tau_b < 100$ ms) but before the thermalization of 3.5 MeV alpha particles born at the end of neutral beam injection ($\tau_\alpha \approx 300-400$ ms) as calculated by TRANSP. The long slowing down time of the alpha particles is indicated by the gradual reduction of the calculated β_α after the end of beam injection, as shown in Fig. 1(b). The passing particle resonance condition for TAEs is

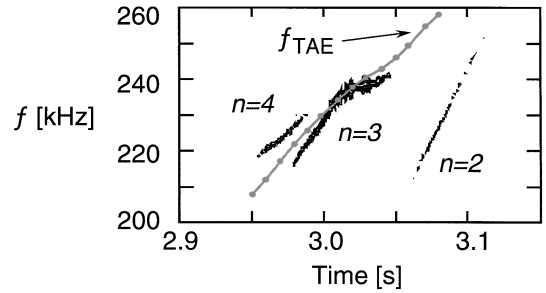

FIG. 2. Contour plot of magnetic fluctuations vs frequency and time for the low $q(0)$ plasma of Fig. 1, indicating multiple TAEs. Also shown is the calculated frequency at $r/a \approx 0.3$ (gray line).

approximately $V_\alpha \approx V_A$ or $V_A/3$, corresponding to the fundamental and first sideband resonance where V_α and V_A are the alpha particle and Alfvén velocity, respectively. For birth velocity alpha particles, $V_\alpha/V_A \approx 1.5$ on the magnetic axis during high power neutral beam injection. The ratio decreases to $0.5 < V_\alpha/V_A < 1$ at the time of peak mode amplitude, as calculated for classically slowing alpha particles born at the end of neutral beam injection. This is in the appropriate range for resonant interaction of passing alpha particles with TAEs in the central region of the discharge.

Evidence for the core localization of mode activity in the low $q(0)$ discharge comes from reflectometer measurements of plasma density fluctuations [21] which are well correlated with edge magnetic measurements (Fig. 3). No coherent mode activity is observed on the reflectometer channels at $r/a \approx 0.57$ or at larger radii; however, the dominant $n = 3$ mode is observed on the innermost channel at $r/a \approx 0.42$. The reflectometer and edge magnetic frequencies are equal, indicating that the two diagnostics observe the same mode. The density fluctuation level $\tilde{n}_e/n_e \approx 1 \times 10^{-4}$ is inferred from reflectometer measurements at $r/a \approx 0.42$, implying a corresponding level of internal magnetic fluctuations $\tilde{B}_\perp/B \approx 10^{-5}$ (using $\tilde{B} \approx B \cdot \nabla\xi_r$, where $\xi_r \approx \tilde{n}_e/\nabla n_e$ is the radial displacement of

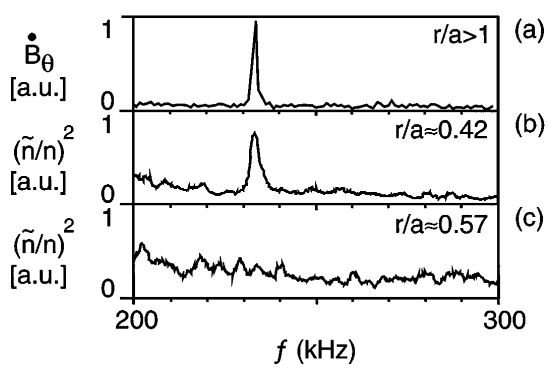

FIG. 3. Spectra of (a) external magnetic fluctuations, (b) reflectometer measurements at $r/a \approx 0.42$, and (c) reflectometer measurements at $r/a \approx 0.57$ for the low $q(0)$ plasma between 3.007 and 3.012 s.

the field line and taking $k_{\parallel} \approx 1/2qR$ for TAEs). This indicates a 10^3 variation in $\tilde{B}/B$ from $r/a \approx 0.4$ to the plasma edge, suggestive of a core localized TAE. From the broadband noise on the reflectometer channels at larger radii, an upper bound on the mode amplitude $\tilde{n}_e/n_e < 4 \times 10^{-5}$ for $r/a \geq 0.55$ is obtained. The estimate of the mode location is also confirmed from the correlation between the variation in the electron density and the variation in the measured mode frequency, which yields the range $0.25 < r/a < 0.45$ for the dominant $n = 3$ mode. The weaker $n = 2$ or $n = 4$ modes are not observed on the reflectometer channels; however, the dominant $n = 3$ mode is already near the limit of detection. TAEs have not been observed on electron cyclotron emission (ECE) measurements, consistent with the weak internal amplitude of the modes based on core reflectometer measurements and the high threshold of detection ($\delta T_e/T_e \sim 1\%$) for ECE.

Alpha-driven TAEs are observed for $\beta_\alpha(0) \approx 0.02\%$ in the high $q(0)$ discharges, and above 0.04% for low $q(0)$ plasmas (Fig. 4). The scatter in the data is possibly due to small variations in the central safety factor following the end of neutral beam injection. Indeed theory predicts that TAE stability is highly sensitive to small variations in $q(0)$ for plasmas with low central magnetic shear [22]. The lost alpha detectors [23] indicate only classical alpha particle loss during TAE activity, consistent with the weak fluctuation level of these modes [2]. There is also no clear evidence for internal redistribution of alpha particles resulting from the TAE activity, based on pellet charge exchange (PCX) [24] measurements of deeply trapped alpha particles in the energy range 1–2.5 MeV, taken 300 ms after the termination of neutral beam injection.

A necessary condition for these modes to be TAEs is that the frequency lies inside the toroidicity induced gap in the shear Alfvén spectrum. The $n = 3$ gap in the shear Alfvén spectrum is calculated using the NOVA-K code for the high and low $q(0)$ cases (Fig. 5) [13]. In the weak shear, high $q(0)$ plasma the $n = 3$ gap is radially open and the observed mode frequency lies near the bottom of the gap, as expected for TAEs. For the low $q(0)$ case the gap is also radially well aligned beyond $r/a = 0.15$, and the mode frequency is again in the gap. This is in contrast to typical supershot plasmas where the gap structure is poorly aligned for low-n modes. The calculated TAE frequency from NOVA-K is 163 and 228 kHz for the high and low $q(0)$ cases, respectively, which are within 5% of the measured frequencies at the time of analysis.

TAE stability analysis is performed using the NOVA-K code which calculates perturbatively the alpha particle drive, the electron/ion/beam landau damping, radiative damping, and collisional damping. Continuum damping is neglected in this case. The balance of alpha particle drive and total damping yields the critical β_α for TAE stability. These calculations are presumed valid so long as the alpha drive and damping rates are small compared to the mode frequency. NOVA-K analysis is performed just prior to the end of neutral beam injection and at the time of peak mode amplitude following termination of high power neutral beams. For comparison, a D-T supershot discharge with similar plasma parameters to the low $q(0)$ discharge ($P_{\rm NBI} = 22$ MW, $B_T = 4.8$ T, $I_P = 1.8$ MA, $R_0 = 252$ cm, $P_{\rm FUS} = 3.5$ MW) is also analyzed before and ~150 ms following the termination of neutral beam injection. For all these discharges NOVA-K computes the most significant modes (largest ratio of alpha drive to total damping) to be of the core localized type occurring inside $r/a = 0.5$, consistent with previous calculations of TAE stability in TFTR [13]. The dominant range of toroidal mode number for the supershot case is $n = 4$–6 and the modes are located inside the $q = 1$ surface. In contrast, the dominant mode numbers for the high $q(0)$ and low $q(0)$ plasmas are $n = 2$–4.

For the low-n modes considered in this Letter, TAEs are calculated to be stable during neutral beam injection in all three discharges, as observed experimentally. The dominant stabilizing influence for low-n modes is beam ion damping on the sideband resonance $V_b \approx V_A/3$ and radiative damping on KAWs which depend on both plasma beta and magnetic shear [13]. Figure 6 displays

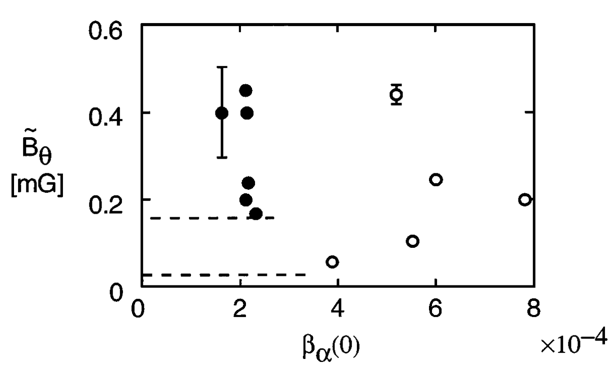

FIG. 4. External magnetic fluctuations level vs $\beta_\alpha(0)$ at the time of peak mode amplitude for high $q(0)$ (solid circles) and low $q(0)$ (open circles) plasmas. The TAE detection limit differs for the two cases due to broadband noise, as indicated by the dashed lines.

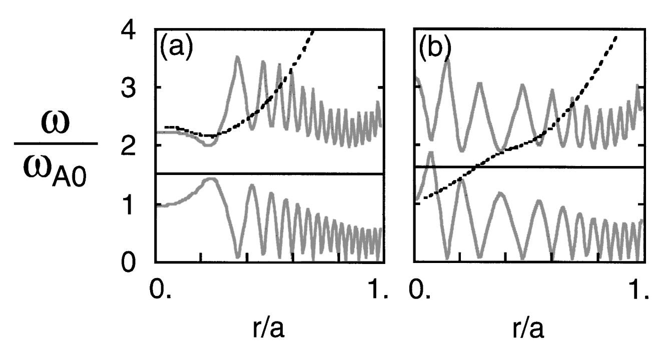

FIG. 5. Toroidicity induced $n = 3$ gap in the shear Alfvén spectrum (gray) and q profile (dashed) vs minor radius for the high $q(0)$ discharge in (a) and low $q(0)$ discharge in (b). Observed $n = 3$ mode frequency (horizontal line) is inside the gap $[\omega_{A0} = V_A(0)/2q_aR]$.

the calculated critical β_α at 150 ms after termination of neutral beam injection for the comparison supershot discharge with $q(0) < 1$, and for the high and low $q(0)$ plasmas with TAE activity in Fig. 1. Also shown is the experimental range of $q(0)$ and β_α in these plasmas. No TAE activity has been observed in supershots following the end of neutral beam injection, consistent with the much larger critical β_α required for TAE excitation. The trend of decreasing critical β_α with increasing $q(0)$ is qualitatively consistent with the experimental observation of TAE excitation with increasing $q(0)$.

Simulations using a Hamiltonian guiding center code ORBIT [25] have been carried out for the $n = 3$ mode in the low and high $q(0)$ cases of Fig. 1. For a total linear growth rate $\gamma/\omega < 0.5\%$ corresponding to maximum alpha drive computed from NOVA-K, the saturated mode amplitude is calculated to be very weak ($\tilde{B}/B \sim 10^{-4}$), consistent with experimental observations. Alpha loss is also expected to be insignificant at this fluctuation level for a single unstable mode [2] as observed in experiment. However, the saturated mode amplitude and corresponding alpha loss are expected to increase dramatically for higher linear growth rates and particularly for multiple overlapping resonances [3]. Sensitivity of the calculated critical β_α to small variations in the central safety factor for $q(0) > 1$ indicates the need for a detailed scan of $q(0)$ in upcoming D-T experiments.

In summary, alpha-driven TAEs have been observed for the first time in TFTR D-T plasmas. These modes follow the end of neutral beam injection in plasmas with reduced central magnetic shear and elevated central safety factor. The experimental results confirm qualitatively the theoretical prediction of alpha-driven TAEs in low magnetic shear, high $q(0)$ discharges following the end of neutral beam injection in TFTR. Further measurements are required in order to confirm the sensitivity of the TAE stability to variations in $q(0)$ and to maximize the mode amplitude for alpha loss studies.

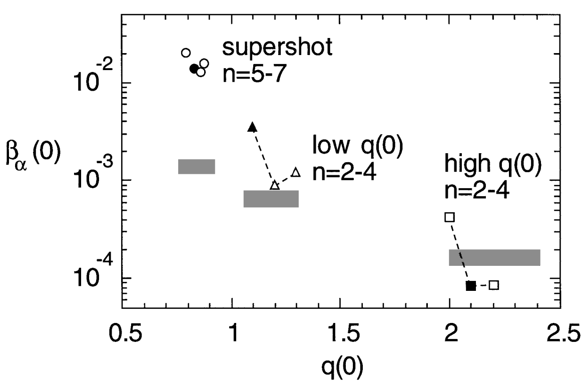

FIG. 6. Calculated critical $\beta_\alpha(0)$ from NOVA-K $\approx$ 150 ms after the end of neutral beam injection for a supershot plasma with $\beta_\alpha \approx 0.15\%$ (circles), low $q(0)$ with $\beta_\alpha \approx 0.07\%$ (triangles) and high $q(0)$ plasma with $\beta_\alpha \approx 0.02\%$ (squares). Solid symbols refer to the equilibrium profile computed from TRANSP with q-profile data obtained from motional Stark effect measurements, while open symbols are for small parametric scans about the measured $q(0)$. The gray regions indicate the range of $\beta_\alpha(0)$ and $q(0)$ computed by TRANSP for these discharges. For the $q(0)$ scan, the q profile at $r/a > 0.5$ is held fixed while the central q is varied monotonically over a range comparable to the experimental uncertainty in the q-profile.

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