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OBSERVATION OF ALPHA-PARTICLE DRIVEN TOROIDAL ALFVÉN EIGENMODES IN TFTR DT PLASMAS*

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ABSTRACT

Toroidal Alfvén Eigenmodes (TAEs) driven by energetic alpha-particle have been observed for the first time in TFTR DT plasmas. These modes occur 100-300 ms after DT neutral beam injection in plasmas with elevated central safety factor and reduced central magnetic shear. TAEs are observed for $\beta_\alpha(0) \geq 0.01\%$ in q(0)>2.0 discharges, consistent with linear stability calculations [IAEA/CN/64/D2-6] for plasmas with elevated q(0) and low beam ion damping. Modes appear in the TAE range of frequencies, 150-250 kHz, with toroidal mode numbers n=2,3,4. From core reflectometer measurements the dominant n=3 mode is localized near r/a≈0.3-0.4 which coincides with the region of large β_α. No enhanced alpha loss or significant alpha redistribution is measured during the TAE activity, consistent with nonlinear simulations for a single core localized mode with weak linear growth rate ($\gamma/\omega < 0.5\%$) and low saturated amplitude $\tilde{B}_\theta / B \sim 10^{-5}$.

1. INTRODUCTION

Continued investigation of Toroidal Alfvén Eigenmodes (TAEs) [1] driven by energetic particles in tokamaks is motivated by the potential for such instabilities to eject energetic alphas from the core of a fusion reactor, possibly leading to first wall damage and/or significant reduction of central alpha heating efficiency. Theoretical predictions of unstable TAEs in ITER [2,3] underscore the need for adequate benchmarking of linear stability, nonlinear saturation and alpha loss calculations. Thus far the characteristics of TAEs and associated fast ion losses have been studied in experiments utilizing neutral beam injection in low field plasmas [4-6] and ICRF heating of an highly anisotropic population of deeply trapped minority ions in DD and DT discharges [7-10]. In these experiments, significant losses of beam ions (up to 50%) and hydrogen minority ions (up to 10%) have been observed, [11] indicating the potential for TAEs to redistribute resonant particles in a fusion reactor.

Initial DT experiments on TFTR have achieved up to 10 MW of fusion power and central $\beta_\alpha(0) \approx 0.33\%$ (shot # 80539), but with no observable TAE activity in external magnetic or internal reflectometer measurements [12]. However, recent theoretical studies have indicated that a new class of core-localized TAEs can be unstable in TFTR DT plasmas under conditions of low beam ion damping, low plasma pressure and weak central magnetic shear [13]. Such core localized TAEs have been observed in high-current H-minority ICRF heated plasmas on TFTR [13,14]. Theory also suggested that elevated central safety factor, q(0)>1, could significantly affect mode stability, as could the rapid cooling of the discharge by use of pellets and large He gas puffs [15]. Previous studies have indicated that the most likely period for observing alpha-driven TAEs is following neutral beam injection, after the slowing down of beam ions ($\tau_b \approx 80-100 ms$) but before the alpha particle slowing down time ($\tau_\alpha \approx 300-500$ ms) [16,17]. These methods aim to affect mode stability by reducing beam and thermal ion Landau damping on the sideband resonance by rapidly cooling of the plasma, enhance alpha particle drive by aligning low-n gaps [located near q≈(m+1/2)/n)] to the peak alpha pressure gradient [18-20], and broaden the mode eigenfunction by reducing central shear [13]. A further advantage of raising q(0) is to maintain a more open gap structure for global TAEs by keeping the Alfvén frequency constant ($n_e q^2 \approx const.$) across the plasma radius. Early attempts at modifying the q-profile by use of a partial plasma growth scenario [21] or by the perturbative cooling of the plasma using pellets and He gas puffs yielded no observable TAE activity in TFTR [22]. In this paper we report the first identification of alpha-driven TAEs in TFTR DT plasmas, observed after neutral beam injection in plasmas with q(0)>1 and with reduced central magnetic shear. Section 2 describes the plasma parameters. Experimental results are presented in Section 3. Section 4 compares experimental results with linear stability [23] and nonlinear saturation calculations for core localized modes.

2. PLASMA CONDITIONS

The main objective of this experiment was to test a fundamental prediction of theory, namely that TAEs could be destabilized with only modest fusion power levels in TFTR through the reduction of central magnetic shear and the elevation of q(0). A number of techniques have been developed for producing plasmas with q(0)>1 on TFTR [24]. In order to achieve a modest increase in q(0) while avoiding strong magnetic shear reversal, the plasma discharge was initiated at large major radius but without early neutral beam injection.

Figure 1 shows the evolution of plasma parameters in a DT plasma (#95796) with strong TAE activity. The discharge parameters are: q(0)≈1.1 (obtained from MSE analysis [25] combined with TRANSP [20] analysis of the current evolution following termination of neutral beams), B_T=5.0T, I_p=2.0 MA, R=2.52 m, P_{NBI}=29 MW and P_{fus}=4.0 MW. Typical plasma parameters ~150 ms after termination of NBI were $n_e(0) \approx 4.3\times10^{19}\,\mathrm{m^{-3}}$, $T_e(0) \approx 6\ \mathrm{keV}$ and $T_i(0) \approx 15\ \mathrm{keV}$. A second plasma condition with higher q(0) and lower ion temperature also produced observable TAE activity with the following plasma parameters: q(0)≈1.9-2.4, B_T=5.3T, I_p=1.6 MA, R=2.60 m, P_{NBI}=26 MW and P_{fus}=2.5 MW. In this case, central plasma parameters ~150 ms following beam injection were $n_e(0) \approx 3.5\times10^{19}\,\mathrm{m^{-3}}$, $T_e(0) \approx 5.3\ \mathrm{keV}$ and $T_i(0) \approx 10\ \mathrm{keV}$. The Alfvén velocities for the two discharges were, respectively, $1.1\times10^{7}\ \mathrm{m.s^{-1}}$ and $1.3\times10^{7}\ \mathrm{m.s^{-1}}$, comparable to the alpha birth velocity $V_{\alpha 0} \approx 1.3\times10^{7}\ \mathrm{m.s^{-1}}$. These discharges are relatively free of large amplitude low frequency MHD activity, and sawteeth are delayed by more than one second following termination of neutral beams, consistent with the MSE measurements of q(0)>1.

Figure 2 shows the evolution of beam ion and alpha particle slowing down velocities for the plasma of Fig. 1. The calculation uses the ion birth velocity before the end of beams, and calculates the slowing down velocity from the end of beam injection. The particle velocities are based on TRANSP calculations of the slowing down times, while the Alfvén velocity is calculated from the TRANSP equilibrium analysis including mass density corrections for the relative concentration of deuterium to tritium in the plasma core. Beam ions are predicted theoretically to damp TAEs through the sideband resonance $V_b \approx V_A/3$. However the rapid decay of the central plasma density indicates that beam damping should not be significant much longer than 20-30 ms following the end of neutral beam injection. For energetic alpha particles to destabilize TAEs, the fundamental resonance condition $V_\alpha \approx V_A$, or the weaker sideband resonance $V_\alpha \approx V_A/3$ should be satisfied for passing particles. From Fig. 2, $V_\alpha/V_A \approx 1.5$ at the end of neutral beam injection, and the sideband resonance condition is satisfied for partially thermalized alpha particles well after neutral beam ions thermalize.

Figure 3 shows q and β_α profiles 150 ms after beam injection for the two cases of interest. The evolution of β_α is based on TRANSP calculations of the classical slowing down of alpha particles, and is consistent with PCX measurements in discharges with monotonic q-profiles [18]. Note that the case of q(0)>2 has lower β_α, however the net alpha drive is predicted theoretically to increase strongly with increasing q(0) and decreasing central magnetic shear [13].

3. EXPERIMENTAL RESULTS

Figure 4 shows the magnetic fluctuation level detected on the external Mirnov coils for the low q(0) discharge of Fig. 1. Multiple modes are observed between 100-200 ms following the end of neutral beam injection with dominant toroidal mode number n=3, with n=4 and n=2 modes at much weaker levels. The n=3 mode is also dominant in the high q(0) discharges. All the modes appear in the frequency range 220-250 kHz and propagate toroidally in the diamagnetic drift direction as expected for TAEs. The peak fluctuation level of 0.5 mGauss corresponds to $\tilde{B}/B \approx 10^{-8}$ at the plasma edge, which is comparable to the TAE fluctuation level observed with 3-4 MW H-minority ICRF heating on TFTR. These modes have only been observed in DT plasmas above a threshold fusion power which differs for the two plasma conditions. From the TRANSP calculations, $\beta_\alpha(0)$ decays by ≈30% from the end of neutral beam injection to the time of peak mode amplitude, whereas β_N decays by up to 80% over the same period. Figure 5a shows the spectrum of edge magnetic fluctuations evaluated over a 1 ms time window centered at 3.014s for the data of Fig.4. The Mirnov spectrum in Fig. 5a shows a strong peak at 234 kHz corresponding to the dominant n=3 mode. Figure 5b and 5c show reflectometer spectra of density fluctuations at r/a≈0.42 and 0.57, respectively. These radial locations correspond to the right hand cutoff layer locations for 135 GHz and 128 GHz microwaves launched into the plasma from waveguide mounted on the outboard midplane of TFTR [26,27]. No coherent mode activity is observed at r/a≈0.57 or at larger radii, however the dominant n=3 mode is clearly observed on the reflectometer channel at r/a≈0.42. From the level of phase fluctuations, and assuming the validity of geometric optics for scattering from very long wavelength modes, an estimate of the density fluctuation level $\tilde{n}/n \approx 1\times10^{-4}$ is obtained. Time series analysis of the core reflectometer and edge magnetic measurements reveal a high correlation coefficient ($\gamma \approx 0.5$), indicating that the two diagnostics observe the same mode with frequency close to TAE frequency $V_A/4\pi qR \approx 250$ kHz, evaluated at r/a≈0.3-0.4. The upward sweep of the mode frequency shown in Figure 4 is consistent with the variation in the Alfvén velocity in the plasma core due to the rapid drop in plasma density after termination of neutral beam injection. At the time of mode activity, the correction due to plasma toroidal rotation is ≈ 5 kHz for the n=3 mode at r/a≈0.3.

From the reflectometer measurement of the density fluctuations in the plasma core, we can obtain an estimate of the corresponding level of internal magnetic fluctuations. Using $\tilde{B} \approx B \quad \xi_r$, where $\xi_r \approx L_n\tilde{n}/n$, and $k_\parallel \approx 1/2\,qR$ for TAEs, we obtain the core fluctuation level estimate $\tilde{B}/B \approx 10^{-5}$. This represents a 10^3 variation in $\tilde{B}/B$ from the plasma core to the vacuum vessel wall, indicative of core localized modes. From the broadband noise on reflectometer channels at larger radii, an upper bound on the mode amplitude of $\tilde{n}/n < 3\times10^{-5}$ for $r/a \geq 0.55$ is determined.

In the high q(0) plasmas, mode activity was observed around 170 kHz on external Mirnov coils with dominant toroidal mode number n=3, although in several discharges an n=2 mode was also observed. The mode amplitude at higher q(0) is comparable to the lower q(0) discharges, but mode activity appears at lower fusion power (≈1.5 MW) and $\beta_\alpha(0) > 0.01\%$. No TAE activity was measured on the reflectometer channels in the high q(0) plasmas. One possible reason is that the reflectometer channels did not penetrate far enough into the plasma core to observe the modes. The present reflectometer frequencies are not ideally suited for core localized measurements in this range of toroidal field. However, if we assume these modes are also localized to the region of large alpha pressure gradient around r/a≈0.3, then we obtain a TAE frequency estimate of ≈180 kHz which matches closely the measured mode frequencies. Figure 6 shows the measured frequencies for all the data at high and low q(0) at the time of peak mode amplitude, plotted against the approximate value of the TAE frequency $V_A/4\pi qR$ evaluated at r/a≈0.3. The Alfvén velocity is lower in the plasma core for the higher frequency modes, due to the higher toroidal field and lower plasma stored energy. However, inclusion of the q values at r/a≈0.3 from MSE and TRANSP analysis recovers the correct scaling with the local TAE frequency. For all the TAEs observed in these experiments, the slowing down velocity of alpha particles satisfy the sideband resonance condition $V_\alpha = V_A/3$. Also, at high q(0) the precessional frequency ω_D of even 1 MeV deeply trapped alpha particle near r/a≈0.3 can be comparable to the TAE frequency, as $n\omega_D/\omega_{TAE} \sim nq^2 E_\alpha$.

Fig. 7 shows the variation of the mode amplitude with fusion power for the case of low q(0) discharges. A rapid increase in mode amplitude is observed with increasing fusion power for these plasmas, expected for modes near marginal stability. However a similar scaling is not obtained for the high q(0) plasmas, partly because of the limited range of fusion power (due to poor confinement) and to the higher variability of the central q (1.9<q(0)<2.4). The alpha particle drive is calculated theoretically to be a very sensitive function the Alfvén continuum gap structure, which is strongly controlled by the q-profile. Indeed, theory indicates that the linear stability of TAEs is highly sensitive to small variation in q(0) for plasmas with low central magnetic shear [28].

No enhancement in alpha loss is observed on the lost alpha detectors during TAE activity, as shown in Fig. 8. These detectors are located poloidally 45, 60 and 90 degrees below the outer midplane and are capable of observing energetic particle losses induced by MHD activity in the plasma core. However, the absence of enhanced loss is not surprising given the very low loss of minority ions for similar amplitude TAEs ($\tilde{B}/B \sim 10^{-8}$) in 3-4 MW H-minority ICRF heating experiments on TFTR. There is also no indication of significant redistribution of deeply trapped alpha particles resulting from the TAE activity, as measured by the Pellet Charge Exchange (PCX) diagnostic [18].

4. LINEAR STABILITY AND NONLINEAR SATURATION

Figure 9 shows the n=3 toroidicity induced gap in the Alfvén continuum for the two cases of interest with q(0)≈2.4 and q(0)≈1.1, together with the measured mode frequency in each of these discharges and the location of the reflectometer channel which observes mode activity in the low q(0) case. The gap structure is calculated using NOVA-K with equilibrium profiles computed by TRANSP. In the high q(0) case (Fig. 9a) the n=3 gap structure is very well aligned from the plasma core to the edge and the observed frequency lies well within the gap. In particular the KTAE frequency at the top of the gap is ≈250 kHz, well above the observed mode frequencies. For q(0)≈1.1 in Fig. 9(b) the gap is closed for the measured frequency, but only in a narrow region in the core of the plasma. Theoretical analysis indicates that the mode is unstable for a modest increasing in q(0) from 1.1 to 1.35. Also, the KTAE frequency is ≈320 kHz, and NOVA-K analysis indicates that the KTAE - as well as the odd TAE mode in the upper limit of the n=3 gap - are stable in these plasmas. The sensitivity of the linear growth rate to small variations in q(0) for a core localized n=3 mode is shown in Fig. 10 for the case of q(0)≈2.0-2.5 and $\beta_\alpha(0) \approx 0.015\%$. At q(0)≈2.4 NOVA-K calculations indicate that the n=3 core mode is unstable. Furthermore, the dominant mode number from NOVA-K in both these discharge conditions is n=3, again consistent with experiment. These results suggest that a detailed q(0) scan is required in order to test theoretical predictions of core mode stability as well as to optimize the amplitude of alpha-driven TAEs in TFTR.

Nonlinear ORBIT [29-31] code simulations of mode saturation and alpha particle loss have been carried out for the low n=3 core mode with $q(0)\approx 1.1$. Figure 11 shows a rapid increase in saturated mode amplitude as a function of input linear growth rate. For $\gamma/\omega < 0.5\%$, corresponding to a reasonable upper bound from the NOVA-K (ignoring all damping terms), the estimate of the saturated mode amplitude from ORBIT analysis is very weak ($\tilde{B}/B \sim 10^{-4}$). This result is consistent with the weak mode amplitude estimated from core density fluctuations ($\tilde{B}/B \sim 10^{-5}$). However, the saturated mode amplitude and corresponding alpha loss are expected to increase dramatically for higher linear growth rates for single modes, and particularly for multiple overlapping modes, [32] as are predicted in ITER.

5. CONCLUSION

Recent DT experiments on TFTR have identified alpha driven TAEs under conditions of elevated central safety factor, reduced central shear and low plasma pressure. These modes have only been observed in DT plasmas with elevated central q. Some characteristics of the modes are : (i) the mode scale with the TAE frequency, (ii) the mode appears in the central region of the plasma near the region of maximum alpha drive, (iii) the modes only appear after neutral beam ions thermalize, but before the slowing down time of the alpha particles (iv) the dominant mode number is n=3 as obtained from linear stability analysis, (v) the saturated mode amplitude is consistent with weak linear growth predicted for these modes. Theory indicates that TAE stability is highly sensitive to q(0), which suggests the need for detailed systematic q(0) scans in future experiments in order to test theoretical predictions and optimize the mode amplitude. Future experiments on TFTR will also be aimed at understanding alpha loss and redistribution induced by alpha-driven TAEs. These studies will enable better theoretical projections of possible TAE instability and resulting alpha loss in ITER.

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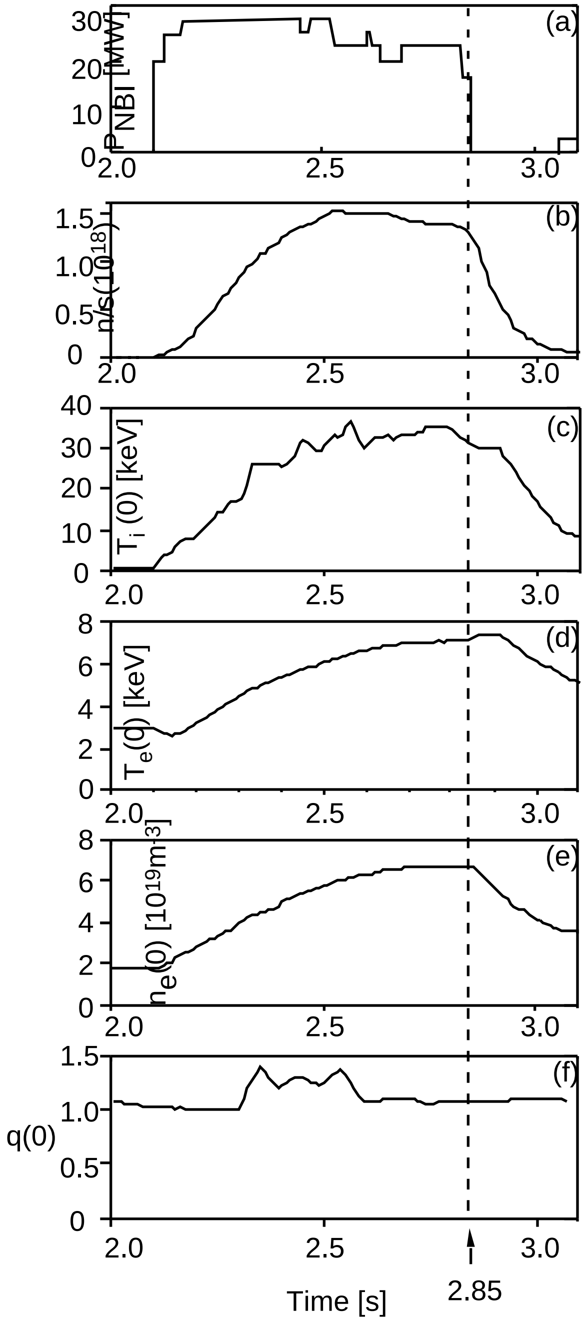

Figure 1. Evolution of (a) neutral beam power (b) DT neutron source rate (c) central ion temperature, (d) central electron temperature (e) central electron density and (f) central safety factor q(0), obtained from a combination of MSE measurements during neutral beam injection and TRANSP simulation. Dashed line denotes time of neutral beam turn off.

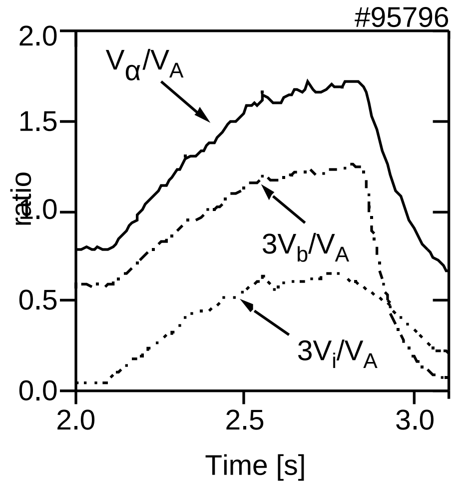

Figure 2. Evolution of the ratio of particle velocity and Alfvén velocity in the center of the discharge for alpha particles (V_α), D and T beam ions (V_b) and thermal ions (V_i).

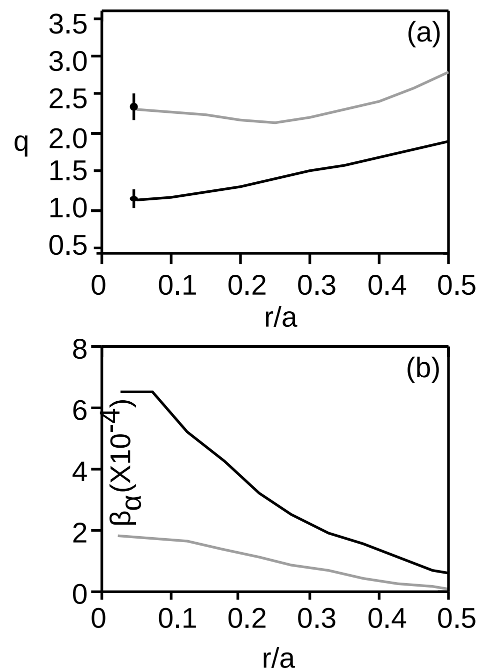

Figure 3. Profiles of safety factor (a) and alpha beta (b) at t=3.0 sec. (≈150 ms following end of beam injection) for the case of high q(0) (dashed line) and low q(0) (solid line) plasmas.

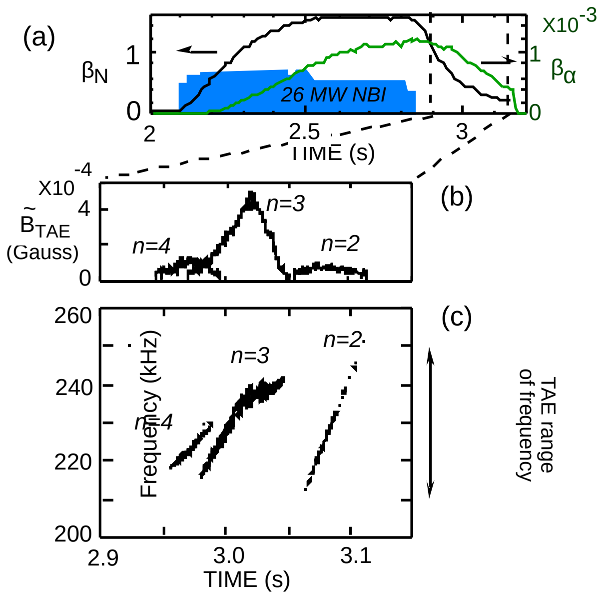

Figure 4. Alpha driven TAEs with q(0)~1.1. Evolution of normalized beta and alpha beta in (a), mode amplitudes of TAE on Mirnov coils following turn off of beam injection in (b), and frequency evolution of modes in (c). The dominant mode number is n=3, and the frequency increase in (c) is correlated with the central density decrease after NBI, expected for Alfvén waves.

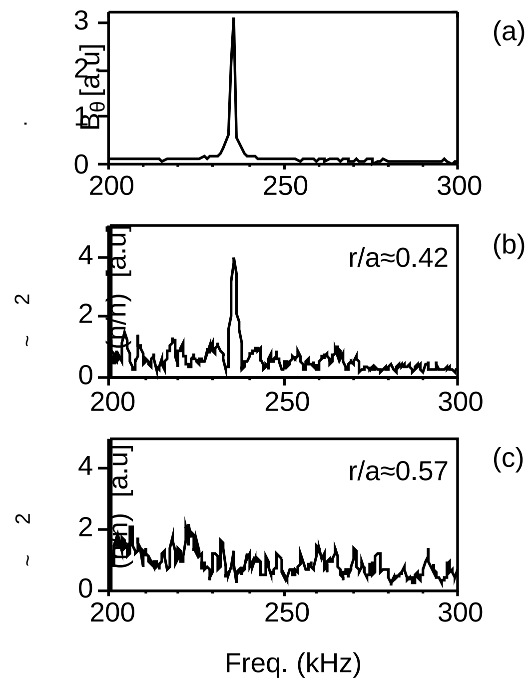

Figure 5. Spectrum of Mirnov signal in (a), reflectometer signal at r/a=0.42 in (b) and reflectometer signal at r/a=0.57 in (c), taken over a 1 ms time window centered at t=3.014 sec. for the dominant n=3 mode in Fig. 4.

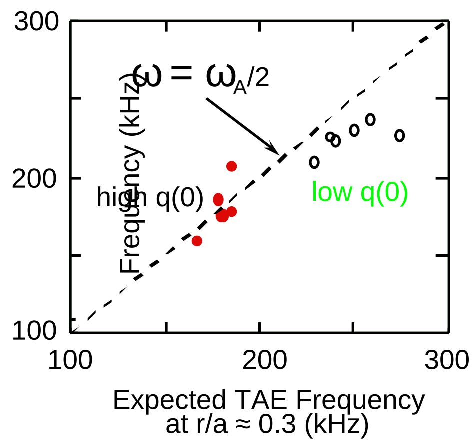

Figure 6. Observed mode frequency scales as $\omega_A/2$ evaluated at r/a≈0.3.

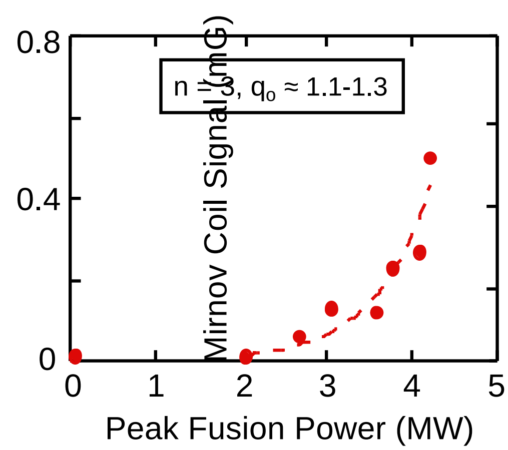

Figure 7. Strong amplitude increase observed on edge Mirnov signals with increasing fusion power, as expected for alpha-driven TAE near threshold condition for instability. Modes are observed with $\beta_\alpha(0)$ > 0.03% for q_o~1.1-1.3.

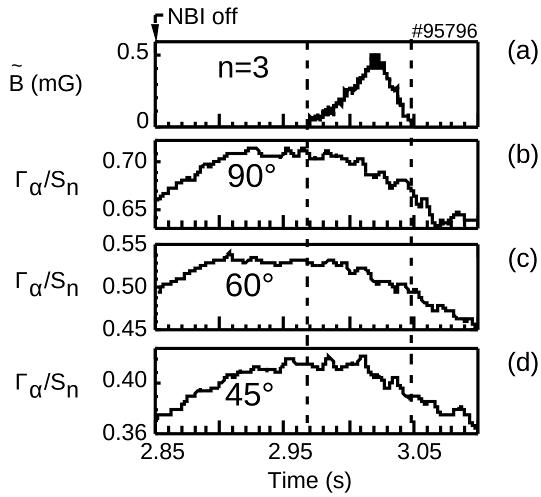

Figure 8. Alpha-driven TAE does not produce measurable α-loss on lost alpha probes. The mode amplitude from magnetics is shown in (a), and the alpha-loss measurements normalized to the DT neutron source rate for the detectors 90°, 60° and 45° below the outer midplane are shown in (b), (c) and (d) respectively.

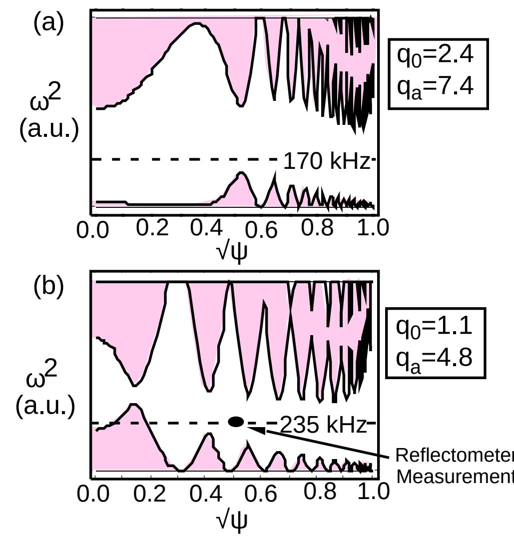

Figure 9. Mode frequency lies Inside calculated gap in n=3 Alfvén continuum for r/a>0.2 in both high q(0) (a), and low q(0) (b) discharges.

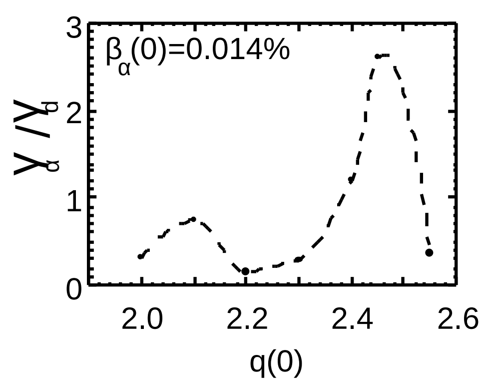

Figure 10. The ratio of drive to damping versus q(0) for n=3 core mode.

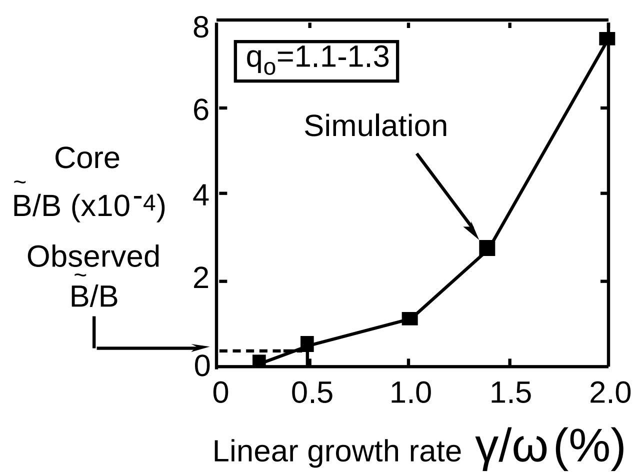

Figure 11. Nonlinear (ORBIT) Simulation of n=3 core TAE predicts saturation at a very low level for weak linear growth rate. The observed mode amplitude is consistent with simulation for γ/ω < 1 % calculated by NOVA-K.