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R. Nazikian, G.J. Kramer, C.Z. Cheng, N.N. Gorelenkov,
H.L. Berk and S.E. Sharapov

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R. Nazikian[1], G.J. Kramer[1], C.Z. Cheng[1], N.N. Gorelenkov[1],
H.L. Berk[2] and S.E. Sharapov[3]

[1]*Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA.*
[2]*Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712 USA.*
[3]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

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ABSTRACT
The original description of alpha particle driven instabilities in the Tokamak Fusion Test Reactor (TFTR) in terms of Toroidal Alfvén Eigenmodes (TAEs) remained inconsistent with three fundamental characteristics of the observations: (i) the variation of the mode frequency with toroidal mode number, (ii) the chirping of the mode frequency for a given toroidal mode number, and (iii) the anti-ballooning density perturbation of the modes. It is now shown that these characteristics can be explained by observing that cylindrical-like modes can exist in the weak magnetic shear region of the plasma that then make a transition to TAEs as the central safety factor decreases in time.
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In a magnetic confinement fusion reactor, the nuclear interaction of deuterium and tritium (D-T) releases a large quantity of energy in the form of 14MeV neutrons and 3.5MeV alpha particles. The neutrons escape from the magnetic field and are captured by a lithium blanket used to generate electricity and breed tritium. The alpha particles are confined by the magnetic field, imparting their energy to the D-T plasma and thus sustaining the thermonuclear burn. The 3.5MeV alpha particles are far more energetic than the thermal ions and their birth velocity is sufficient to excite Alfvén instabilities. The Alfvén modes perturb the alpha particle orbits and may expel alpha particles before they deposit their energy to the plasma, potentially damaging plasma facing components and reducing the efficiency of plasma self heating. These concerns motivate the study of alpha particle driven instabilities in fusion experiments.

Deuterium-tritium experiments on the Tokamak Fusion Test Reactor (TFTR) provided the very first opportunity to investigate the excitation of Alfvén waves by fusion alpha particles under reactor relevant conditions [1, 2]. The original observation of alpha particle driven instabilities in TFTR was reported as evidence for the existence of alpha-particle-driven Toroidal Alfven Eigenmodes (TAEs) [3]. TAEs are resonant cavity modes in the toroidal plasma residing within frequency gaps in the shear Alfvén continuum spectrum [4].

Figure 1 shows data for a typical TFTR D-T discharge in which high frequency magnetic oscillations were observed in the after glow of the discharge. The afterglow is the period of time following the termination of intense neutral beam heating. These oscillations were observed in discharges where the penetration of the inductively driven current into the plasma core was delayed by preheating the plasma during the current rise [5]. The delayed current penetration creates regions of weak central magnetic shear, which is anticipated to occur in future steady state fusion reactors with large non-inductive current drive. The mode frequencies observed on external magnetic probes were consistent with theoretical calculations for TAEs. However, internal measurements of the same modes exhibited anomalies in frequency and mode structure that were in conflict with TAE theory and these anomalies remained unreconciled until now. Here we report the reconciliation.

The frequency anomalies in the TFTR data can be seen in Fig. 2 which shows the temporal evolution of the mode frequency with time as observed on external magnetic probes (red) and internal reflectometer measurements (blue). The internal reflectometer signals are obtained from the change of the phase of a microwave beam reflecting from the core of the plasma [6, 7]. The magnetic signals (red) measured outside the plasma clearly peak around the TAE frequency. However, the core reflectometer signals (blue) indicate that the modes originally emerge at lower frequencies in the plasma core and then chirp up to the TAE range of frequency where they are observed on the magnetic probes. This frequency shifting character is a property of all the TFTR D-T shots that exhibited Alfvénic activity driven solely by alpha particles and which require the special current profile preparation described above. The data indicates that the spatial structure of the mode is evolving in time from a core localized to a global (radially extended) mode as the TAE frequency is approached. As indicated in Fig. 2, the central safety factor gradually decreases during this period as the toroidal plasma current continues to penetrate into the core. Within the context of TAE theory, the modes should have a far smaller frequency variation in the core of the discharge where the central safety factor is roughly uniform. An attempt to maintain a TAE based explanation with the assumption that frequency may change due to steep density gradients in the plasma profile, temporal changes in time or from plasma flow effects, are incompatible with the data. The core density has a flat profile, the density is rather steady in time (less that a 5% variation) and the plasma flow is small.

The complexity of the observed mode activity in the plasma core cannot be encompassed by TAE theory alone. In particular the evolution of the mode frequency from internal oscillations (blue) toward the TAE frequency detected by external magnetic signals (red) is reminiscent of the chirping behavior of so-called Alfvén Cascades observed in JET and JT-60U plasmas with reverse and weak central magnetic shear [8,9]. Here we shall also refer to the chirping phase of the modes in TFTR as Cascade modes. Originally an explanation of the Alfvén Cascades was attributed to a non-perturbative contribution of energetic particles that was needed to create the mode and produce only up-chirping behavior as the central q-value decreases in time [10]. This picture was confirmed and extended to account for instability drive [11]. However, numerical calculations showed that ideal MHD theory in toroidal geometry can produce such behavior as well [12-15] and an analytic theory that describes the contribution from both effects has been developed [16]. Theory predicts that these modes should be cylindrical-like in that they are dominated by a single poloidal harmonic number m (much like the well known Global Alfvén Eigenmode) unless the frequency is close to the toroidicity induced frequency gap, whereupon one obtains a toroidal-like mode where two successive poloidal harmonics dominate the structure of the eigenmode, called the Toroidal Alfvén Eigenmode. The cylindrical mode has a frequency close to the shear Alfvén frequency associated with the surface on which the magnetic shear (nearly) vanishes and the mode is localized there. Such surfaces of mode localization certainly occur when there is shear reversal but also when there is a flat shear profile about the toroidal axis. This has been confirmed by detailed numerical simulation, presented here, and analytically in ref. [17]. In contrast to the strongly reversed magnetic shear discharges in JET and JT-60U where similar modes were identified, the TFTR discharges considered here have a nearly flat q-profile in an extended region of the central plasma cross section (see Fig. 1d and note that the small depression in the reconstructed experimental q-profile is not statistically significant). In TFTR the partial pressure of alpha particles is quite small so that we expect that modes to exist without the presence of energetic particles, as is shown in Fig. 3. Figure 3 shows the NOVA-K calculation of the continuum spectrum together with the frequency, location and radial extent of the Cascade mode for the n=2 mode corresponding to the q-profile in Fig. 1. Note that the mode frequency is just above the continuum and well below the TAE frequency. Because of the weak magnetic shear, the mode does not intersect the continuum so that the damping is expected to be weak.

Both the CASTOR [18] and the NOVA-K [19, 20] codes were used to study the frequency behavior of the Cascade modes observed in TFTR and their transition to the TAE with the relevant plasma parameters and profiles obtained from the analysis of the TFTR data. A comparison of the numerical results with the TFTR data is shown in Fig. 2. The CASTOR and NOVA-K solutions are in good agreement. When q_0 is too large for TAEs to appear ($q_0 > (m - 1/2)/n$ for given m and n values) the Cascade modes are found. The calculations show that Cascade modes in TFTR consist of one dominant poloidal harmonic (a characteristic of Cascade modes away from the TAE gap) with mode number $m=2n$ and are localized in the central weak magnetic shear region of the discharge where the alpha particle drive is greatest. We see in the figure that the Cascade mode frequency increases rapidly with decreasing q_0 until the mode frequency approached the TAE frequency. At this point the Cascade mode transforms into the TAE by coupling to the additional poloidal harmonic $m=2n-1$. When q_0 decreases further the TAE becomes more global and is eventually damped. The transition from the core localized Cascade mode to the more radially extended TAE is consistent with the observed increase in edge magnetic signals as the TAE frequency is approached in Fig. 2.

To calculate the density perturbation associated with the mode we need to evaluate the ideal MHD compression based on the formulation of Ref.19 (see Eq.3.54 in that reference). We will also neglect the parallel perturbed magnetic field, which is a valid approximation for low beta plasmas. This leads to $\nabla \cdot \xi \approx -2(\hat{\mathbf{n}} \bullet \xi)(\hat{\mathbf{n}} \bullet \boldsymbol{\kappa})$ where ξ is the magnetic field line displacement, $\hat{\mathbf{n}}$ is the density unit vector normal to the magnetic surface, $\boldsymbol{\kappa} = \hat{\mathbf{R}}/R$, where $\hat{\mathbf{R}}$ is the unit vector along a major radius direction *and* R is the major radius. On the equatorial plane we can write,

$$\frac{\delta\rho}{\rho} = -\nabla \cdot \xi - \xi \cdot \frac{\nabla\rho}{\rho} \cong \left(\frac{-2\hat{\mathbf{R}}}{R} + \frac{\hat{\mathbf{n}}}{L_\rho} \right) \cdot \xi \qquad (1)$$

where the approximation in Eq. (1) is written in the low plasma beta limit, ρ is the plasma density and L_ρ is the density scale length. The second term in brackets in Eq.(1), the convective term, is antisymmetric about the magnetic axis whereas the first term, the compressional term, is symmetric leading to partial cancellation of the density fluctuation level on the low field side of the magnetic axis. Note that the density scale length is comparable to the major radius in these TFTR D-T discharges. As a result, the compressional term is of the same order as the convective term. The symmetry of the density perturbation is therefore expected to be strongly anti-ballooning (peaking on the high field side of the magnetic axis at negative minor radius) even though the magnetic perturbation is symmetric about the magnetic axis for a cylindrical-like mode.

These observations are used in Fig. 4 to show a resolution of an apparent anomaly in the TFTR data concerning the purely anti-ballooning structure of the lowest frequency $n=2$ mode as observed on the core reflectometer diagnostic. The outstanding feature of this data is the near total absence of mode activity on the low magnetic field side of the plasma. The NOVA-K calculation of the perturbed density exhibits an antiballooning feature which closely resembles the antiballooning feature observed on the reflectometer response for the $n=2$ mode. This similarity indicates that the asymmetry of the observed density perturbation is consistent with the signal expected for Cascade modes along the plasma midplane from NOVA-K calculations, and quite unlike that expected for TAEs.

The transition from a core localized cylindrical mode to a more global outward ballooning TAE is shown in Fig. 5. As the mode frequency approaches the TAE frequency for the n=4 mode in Fig. 2, the mode amplitude at positive radii dominates over negative radii, as expected for TAEs with strong coupling of the $m-1$ and $-m$ poloidal harmonics when $-(m-1/2)/n \sim q_0$, the q-value on axis. This transition in the data is consistent with the NOVA-K calculation shown in Fig. 5c. Note that the NOVA-K simulation shows that the mode structure becomes more global and couples better to the plasma boundary as the mode frequency increases, consistent with the increase in the magnetic signal compared to the reflectometer signal shown in Fig.2. In conclusion, the TFTR D-T experiments exhibit Cascade modes even when the q-profile is flat at the center rather than being strongly reversed. As the central q-value decrease in time these mode convert into TAEs, as predicted in theoretical and numerical calculations.

We are now left to ponder the implications of this new understanding for fusion reactors. It is important to note that the dominant modes observed in the TFTR experiments are Cascade modes. TAEs were observed only after the appearance of the Cascade modes and they were rapidly damped in amplitude after the transition from the Cascade to the TAE. This may be due to the more radially extended nature of the TAE which can enhance its damping by coupling to the periphery of the discharge where there are few alpha particles. The Cascade modes should be especially important for the advanced tokamak reactor concept which requires high levels of off-axis non-inductive current drive leading to broad regions of weak magnetic shear. If the alpha particle birth population is sufficiently extended to encompass the region of weak magnetic shear, then Cascade modes are likely to emerge.

There was no discernable increase in alpha particle losses during Cascade mode activity in the TFTR DT experiments. However, careful analysis of the stability, non-linear growth and coupling of multiple Cascade modes is needed in present scale experiments in order to predict their behavior in a burning plasma.

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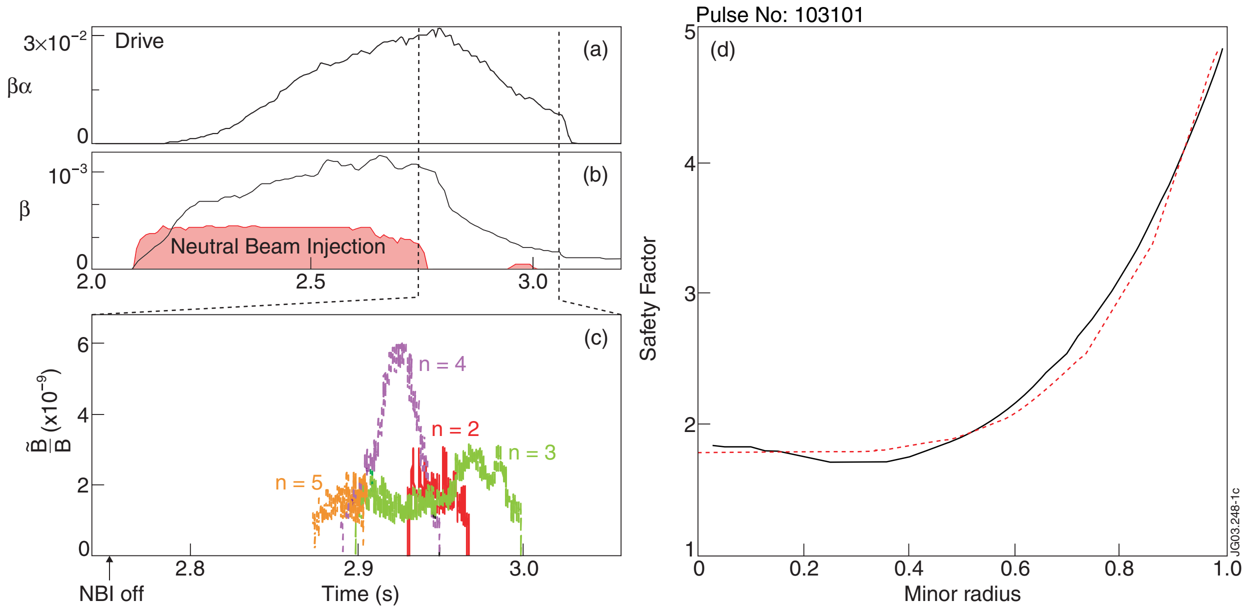


Figure 1 : Time history of the central alpha particle pressure (a) with the neutral beam heating duration also indicated. The central plasma pressure is shown in (b) for comparison. The time history of the magnetic fluctuations is indicated in (c) where a range of toroidal mode numbers are observed in succession from n=5 to n=2. The experimentally reconstructed q-profile is shown by the solid curve in (d) where the weak central magnetic shear is indicated by the flatness of q-profile in the core. A centrally flat q=profile used in the calculations discussed below is shown by the dashed curve. The plasma has the following machine parameters: major radius 252cm, plasma toroidal current 2.0 MA, Toroidal magnetic field 5.3T.

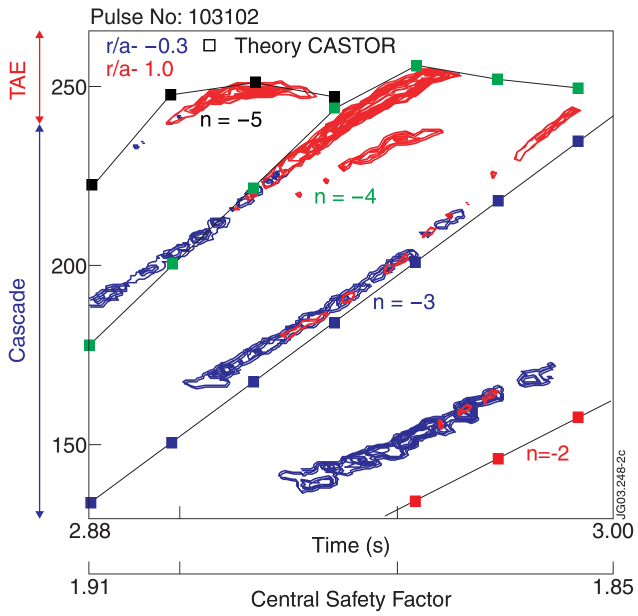
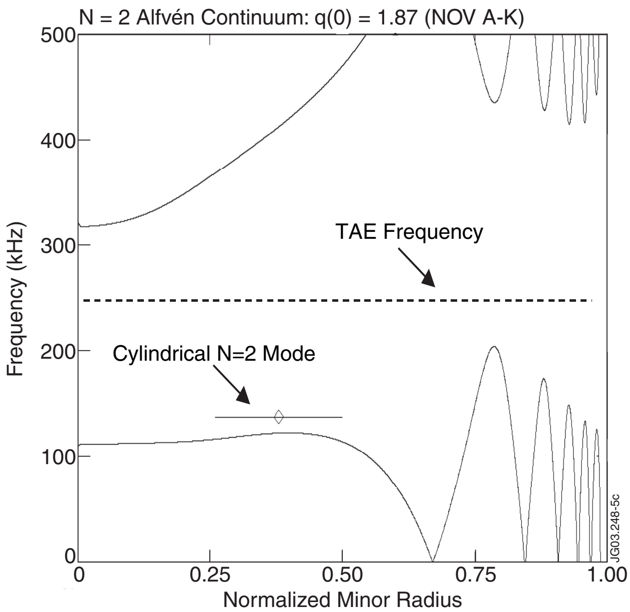


Figure 2: Contour plot of edge magnetic measurements (red) and core density fluctuations using an X-mode reflectometer (blue) for the discharge in Figure 1. The reflectometer measurements are located at a normalized minor radius of −0.3. Also indicated is the range of expected mode frequencies for TAEs and the range of mode frequency expected for Cascade modes. Rectangles indicate CASTOR code calculations of the mode frequency expected for Cascade modes using the measured plasma equilibrium and evolving the central safety factor over a narrow range near q=2.



Alfvén continuum frequency vs. normalized radius for toroidal mode number n=2 and q(0)=1.87 in Figure 2. The radial extent of the n=2 cylindrical mode is indicated by the horizontal line. The n=2 mode frequency is well below the TAE frequency, however the mode does not intersect the continuum.

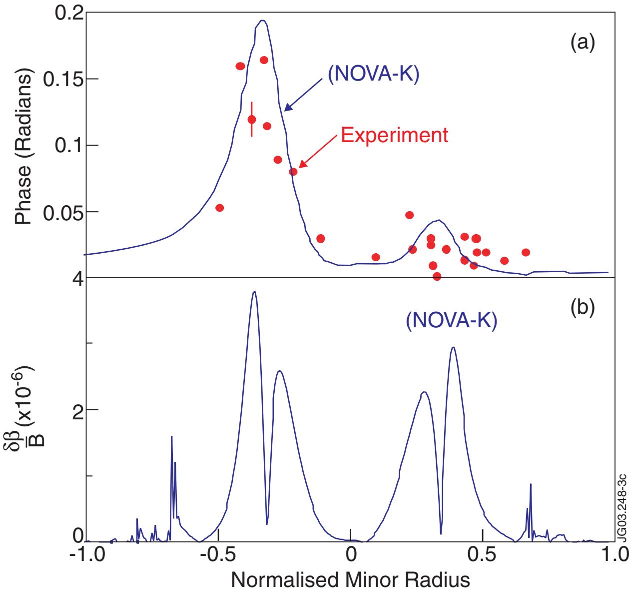


Figure 4: Measured radial structure of density fluctuations (a) for the n=2 mode in Figure 2 compared to the theoretically expected radial mode structure for the n=2 Cascade mode according to the NOVA-K code. In (b) the magnetic fluctuation level |dB/B| from NOVA-K is also shown, indicating the cylindrical nature of the mode from the near equal amplitude on the high and low field side of the magnetic axis.

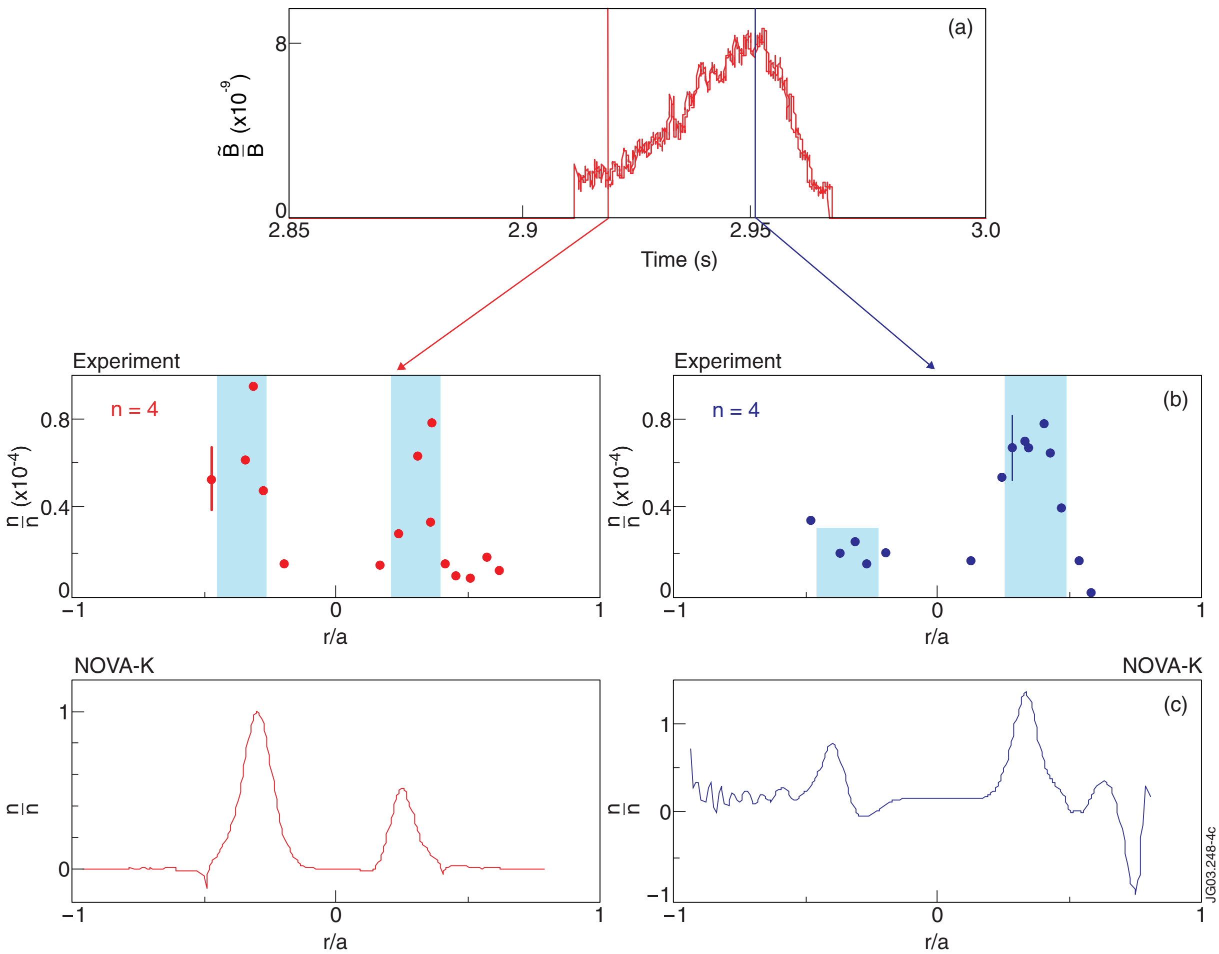


Figure 5: Time evolution of edge magnetic fluctuations for the n=4 mode in Figure 2 (a). The radial density fluctuation profile using the reflectometer diagnostic is shown in (b) early (left) and later (right) in time, and radial density eigenmode expected for the n=4 Cascade mode (left) and TAE (right) in (c).