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Experimental Study of Toroidicity-Induced Alfvén Eigenmode (TAE) Stability at High q(0)

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Experiments to destabilize the Toroidicity-induced Alfvén Eigenmode (TAE) by energetic alpha particles were performed on the Tokamak Fusion Test Reactor using deuterium and tritium fuel. To decrease the alpha particle pressure instability threshold, discharges with an elevated value of q(0) > 1.5 were used. By raising q(0), the radial location of the low toroidal-mode-number TAE gaps moves toward the magnetic axis and into alignment with the region of maximum alpha pressure gradient, thereby (in theory) lowering the value of the central alpha particle β_α required for instability. No TAE activity was observed when $\beta_\alpha(0)$ reached 0.08% in a discharge with fusion power of 2.4 MW. Calculations predict that the alpha-driven TAE was weakly unstable.

1. Introduction

Accurate prediction of the effects of a large alpha particle population on collective instabilities is a prerequisite for the design of a fusion reactor. Of particular concern is the alpha-driven toroidicity-induced Alfvén eigenmode (TAE).[1] In an ignited tokamak like the International Tokamak Experimental Reactor (ITER), the TAE instability could lead to large losses of fusion alpha particles which could quench the burning plasma or damage the first wall of the reactor. Relevant experiments can be performed in the Tokamak Fusion Test Reactor (TFTR)[2] when using deuterium and tritium (DT) as fuel. One of the initial goals of the DT TFTR experiments was to create alpha-driven TAE modes in order to validate the existing TAE stability codes. These codes could then be more confidently applied to TAE stability calculations for a reactor.

The threshold for excitation of the alpha-driven TAE instability has been difficult to reach in TFTR. Even the discharges with the highest production of fusion power[3] attained on TFTR reach only a modest value of $\beta_\alpha(0) \approx 0.33\%$. There is also poor alignment between the low-n TAE gaps, where n is the toroidal mode number, and the maximum in the alpha pressure gradient. Consequently, typical TFTR discharges are calculated to be stable to the TAE instability.[4,5] Various experiments have been performed to reduce mode damping and therefore the mode threshold. For example, ion Landau damping was calculated to be a dominant damping mechanism for low-n alpha-driven TAE modes in TFTR supershots.[6] Experiments which rapidly decreased the ion temperature and damping using He gas puffing or pellet injection were performed.[7,8] No clear indication of alpha-driven TAE activity was observed. More recent analysis of these experiments suggest that the Landau damping of the D beam ions was dominant and the alpha pressure in the experiment was not sufficient to exceed the TAE instability threshold.[5,7]

This paper reports the result of an experiment following a different approach to lowering the TAE threshold by better alignment of $\beta_\alpha(R)$ and q(R).[4] Analysis of standard [q(0) < 1] DT supershots[4,5] has shown that the low-n TAE structure is normally localized in the outer half of the plasma minor radius, where the alpha particle drive is relatively low. The alpha drive can not be easily moved to this location due to the peaked neutron source profile of supershots. By increasing the value of the central safety factor, q(0), the radial location of the TAE gaps move inward and are aligned more closely with the location of the maximum alpha pressure gradient. The result is higher growth rates and lower $\beta_\alpha(0)$ thresholds. A more detailed description of this approach is given in reference [4].

In the experiment, high q(0) was obtained but no enhanced TAE activity was observed. The details of this experiment are presented in the following section. Measurements made of the TAE signatures by three independent diagnostic instruments are presented in the third section. The final section presents the TAE stability analysis and some conclusions to be drawn from this experiment.

2. Experiment

Typical TFTR supershots have values of the safety factor, q(0), less than 1.[9,10] Alternative discharge scenarios, however, have been developed to produce $q(0) > 1$ by initiating the discharge with: (1) large major radius in order to have a lower initial current density at the magnetic axis, (2) low plasma current, and (3) neutral-beam injection that is initially predominantly in the direction of the plasma current to maximize the off-axis beam-driven current.[9] A discharge with geometric axis R = 2.60 m, magnetic field B_T = 4.8 T, and plasma current I_p = 1.0 MA was developed with 8.1 MW of neutral beam injection beginning at 2.5 sec composed of 5.6 MW T and 2.5 MW D. The ratio of beam power injected in the direction of the plasma current to that injected counter was adjusted to the value 2:1 in order to reach the desired value of $q(0) \approx 1.5$. As can be seen in Fig. 1, this resulted in a relatively high value of $q(0) > 1.3$ which rose gradually over time. The plasma current was increased to 1.8 MA at a rate of 1.6 MA/sec beginning at 3.0 sec to reduce first orbit and ripple loss of the alpha particles and to increase the β limit to allow more alpha power production. The small decrease in the plasma current beginning at 4.2

sec was designed to stabilize external kink modes by lowering the edge current density. These current ramps had little effect on the value of q(0).

To maximize the fusion power, an additional 10 MW of neutral-beam power were injected into the plasma between 3.7 and 4.5 sec. The resulting total of 18 MW was slightly co-dominated with the co-injected portion being 2.5 MW D and 8 MW T for a total of 10.5 MW while 4.7 MW D and 2.8 MW T were injected in the counter direction. The increased heating produced a peak rate of $\approx 8 \times 10^{17}$ neutrons/sec, or a peak fusion power of 2.4 MW.

A critical parameter in evaluating the shear Alfvén continuum gap structure is the q profile.[5] The poloidal magnetic field was measured using a twelve-channel motional-Stark-effect (MSE) polarimeter.[11,12] This data, along with magnetic and kinetic profile data, was used by the free-boundary equilibrium code VMEC[13] to determine the q profile evolution. The calculated q profile is shown in Fig. 2 at t = 4.36 sec, the time of maximum attained β_α. The magnetic axis was at R_{mag} = 2.73 m and q(0) = 1.51 ± 0.26.

The other critical parameter needed to evaluate the TAE stability is the radial profile of β_α, Fig. 3. This parameter is calculated by the time-dependent interpretive transport code TRANSP.[14,15] The peak value of $\beta_\alpha(0)$ is calculated to be 8×10^{-4} with a volume average of $<\beta_\alpha> = 8 \times 10^{-5}$. This calculation does not include the effect of alpha particle ripple losses. Uncertainty in $\beta_\alpha(R)$ due to uncertainties in the measured density and temperature profiles or to the TRANSP mapping of these measurements to flux coordinates have not been quantified. A rough estimate is that $\beta_\alpha(0)$ is uncertain to ± 20%. The β_α profile is localized in the core of the plasma with a half-width at half maximum of 0.21 m compared to a minor radius of 0.93 m. The peak in the gradient of $\beta_\alpha(R)$ is located at a major radius of 2.94 m which is a minor radius of 0.21 m.

3. Results

Signatures of the TAE instability were monitored by three independent diagnostics: The microwave reflectometer,[16] the Mirnov coil array,[17] and the escaping alpha particle detectors.[18] These instruments have been successful in detecting both beam-driven and ICRF-driven TAE instabilities.[5,17,19] The reflectometer observed no coherent mode activity in the Alfvén range of frequencies between 200 and 400 kHz at normalized minor radii of 0.3 and 0.5 r/a.

A small-amplitude magnetohydrodynamic (MHD) mode in the Alfvén range of frequencies was observed with the Mirnov array for the same discharge as Fig. 2.[17] At 4.0 sec, this mode had a frequency of about 300 kHz which decreased to about 200 kHz beginning at 4.25 sec as shown in Fig. 4. This mode belongs to a class of MHD activity called the “Alfvén Frequency Mode” or AFM and is common on TFTR.[20] It is not a TAE driven by energetic particles. AFM’s have been seen in Ohmic discharges, after pellet injection, during neutral-beam heating, and during ICRF heating.

The characterizing feature of an AFM is the frequency evolution of the mode. As for any Alfvén mode, the frequency is inversely proportional to the square root of the electron density as $n^{-1/2}$. The electron density is increasing throughout the plasma during the time period shown in Fig. 4. In the core of the plasma, the rate of density increase is constant. At the edge of the plasma, the rate of density increase gets larger at about 4.25 sec. This is mirrored in the data: At about 4.25 sec, the frequency of the mode decreases as the inverse square of the edge density. The mode of Fig. 4 is thus identified as an AFM rather than an alpha-particle-driven TAE because the frequency evolution is determined by the density evolution at the edge where there is no alpha-particle drive, rather than at the core where the alpha particles could drive the TAE unstable. In TFTR, only the core-localized TAE’s are expected to be driven by the alpha particles due to the localization of the alpha particle pressure, Fig. 3. [5]

The rate of alpha particle loss to the wall was measured by the set of 3 escaping alpha particle detectors.[18] The alpha collection rate at 90° below the plasma midplane is shown in Fig. 5. The detectors at 45° and 60° below the midplane showed similar results. The 90° detector recorded the loss of alpha particles with pitch angle between 45° and 83° and gyroradius between 2 and 11 cm.

The high-power heating phase and large increase in neutron production began at 3.7 sec, 0.5 sec before the increase detected by the escaping alpha particle detectors. The small, 20%, increase in loss rate after 4.2 sec is interpreted as being due to changes in the total current and current profile, not to any TAE activity. The increase in loss rate during the downward current ramp is in reasonable agreement with the predicted first orbit loss rate as calculated by the ORBIT code.[21] This code integrates the Lorentz force equation to trace the alpha particle orbit under the influence of the tokamak external fields, the internal fields as measured with the MSE polarimeter, and the measured neutron profile. The results of this modeling are shown as the circles in Fig. 5. In contrast, when a strong TAE was driven by ICRF minority tail ions, the loss rate of tail ions increased by a factor of 5 to 8.[22]

In summary, no coherent mode was measured by the microwave reflectometer, only the usual AFM was observed by the Mirnov coil array, and no increase in the lost alpha particle rate above that expected due to the decrease in current was observed. We therefore conclude that no perceptible alpha-particle-driven TAE was excited in this discharge.

4. Discussion and Conclusion

The TAE stability for this discharge has been calculated for toroidal mode numbers n = 1, 2, 3, and 4 using a gyrofluid model, TAE/FL.[4,23,24] The calculation used the q and pressure profiles from the VMEC-generated equilibrium. To determine the damping (including radiative damping) and growth rates of the TAE, the TRANSP calculations of the radial profiles of the electron and ion density, alpha pressure, and neutral-beam pressure profile[15] were used. The TAE growth rates are shown in Fig. 6. Even with the modified q profile and elevated value of q(0), the achieved $\beta_\alpha(0)$ barely reached the predicted threshold for excitation of the TAE. That threshold, however, has been reduced by almost an order of magnitude from a typical TFTR supershot.[4] According to the analysis shown in Fig. 6, a doubling or tripling of the fusion power would have raised $\beta_\alpha(0)$ well above the threshold for n = 1 instability. The dependence of the $\beta_\alpha(0)$ threshold value on q(0) is shown explicitly in reference [4].

Although Fig. 6 shows that the n = 1 threshold was surpassed in the experiment, it is not surprising that no mode was observed for the following reasons. The calculations shown in Fig. 6 should be viewed as a lower bound because several damping mechanisms have not been included.[4] Also, as previously discussed, there is about a 20% uncertainty in the calculation of $\beta_\alpha(0)$. Finally, the small linear growth rate at this $\beta_\alpha(0)$ may be inadequate for the mode to be observed.

Calculation of the $\beta_\alpha(0)$ threshold using the experimental profiles was also made using the global kinetic/MHD stability code NOVA-K [1] and are shown in Fig. 7. It was found that the n = 3 mode was most unstable in this plasma. The n = 1 stability was not considered because, in this case, the code could not properly resolve the mode due to a continuum resonance. The calculated growth rate is a factor of 4 too small to overcome the damping of the TAE. The NOVA-K calculations are also in agreement with the gyrofluid code conjecture that raising q(0) lowers the TAE threshold, although the sensitivity of NOVA-K to changes in q(0) is much less. Unlike the TAE/FL code, NOVA-K did not include a calculation of radiative damping, which is expected to be as large as beam ion damping. Therefore, the growth rate is expected to be lower than that shown in Fig. 7.

While in qualitative agreement, the two codes calculate different $\beta_\alpha(0)$ thresholds for the alpha-driven TAE. One cause may be that the two codes include different damping mechanisms. For example, NOVA-K contained neither radiative nor continuum damping. It is also a perturbative calculation (*i.e.*, uses ideal MHD eigenfunctions) whereas TAE/FL is non-perturbative (uses self-consistent eigenfunctions). This leads to different damping rates even for damping effects that are included in both calculations. While there are differences in the two codes, the exact cause of any difference in the results is not understood. Further discussion of these differences are contained in references [8] and [4].

The experiment that was performed was not a strenuous test of the predictions because of the low $\beta_\alpha(0)$ achieved. Raising the beam power during the heating phase would have raised the fusion power production. If the beam power were 30 MW instead of 18 MW, up to 5.7 MW of fusion power could be generated which would increase $\beta_\alpha(0)$ by a factor of about 2.4 to 0.19%. However, more beam power would also lead to more damping of the mode by beam ions so that the threshold $\beta_\alpha(0)$ value may also change. Discharges with higher beam powers were attempted, but the fusion power was limited by large carbon blooms during neutral-beam injection. Higher power experiments could be performed in the future using recently developed discharge scenarios that allow up to 25 MW of neutral-beam injection into high-q(0) plasmas without blooming.[25]

It has also been found that the addition of very early beam injection before the main heating pulse produces a plasma with large regions of negative shear. Recent calculations with the NOVA-K code suggest that low or slightly negative shear could further lower the $\beta_\alpha(0)$ threshold for the core localized TAE. Calculations with the gyrofluid code have shown that the Global Alfvén Eigenmode (GAE) can also be destabilized by negative shear in the core of TFTR plasmas.

In conclusion, DT experiments were performed on TFTR to drive toroidicity-induced Alfvén eigenmodes with alpha particles. In order to lower the alpha particle pressure threshold, discharges with higher values of q(0) than typical supershots were used. No TAE's were observed using microwave reflectometery or a Mirnov array and no enhanced losses of alpha particles were observed on the escaping alpha particle detectors. TAE stability analysis showed that the moderate fusion power produced by this discharge produced a central alpha particle pressure that barely surpassed the instability threshold. The threshold, however, had been reduced by about a factor of 10 as calculated by a gyrofluid code. Therefore, higher fusion powers are needed to adequately test the hypothesis of lowered TAE thresholds by increased values of q(0).

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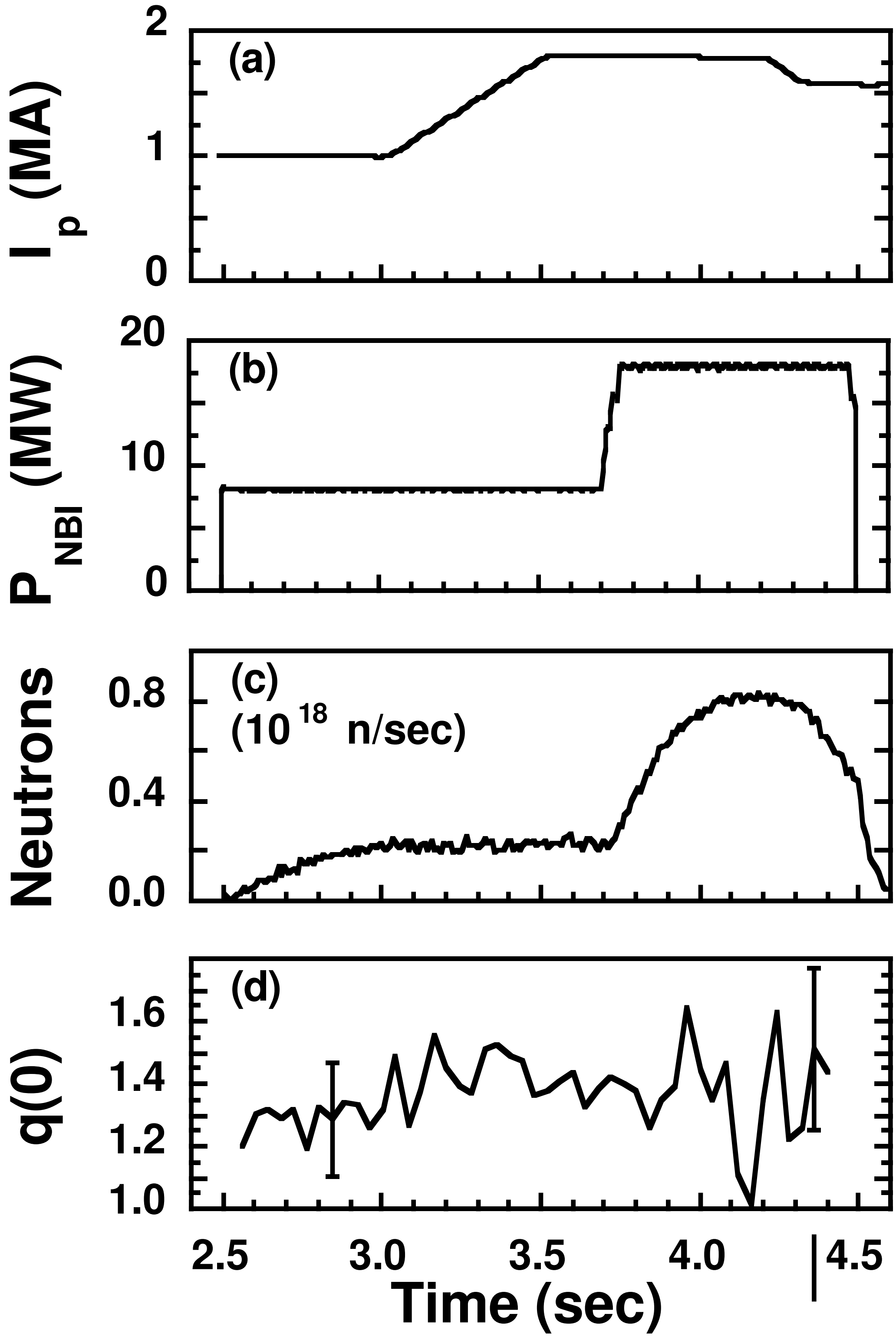

Fig. 1. Plasma parameters for TFTR discharge 80788. Shown are (a) plasma current, (b) neutral-beam injected power, (c) neutron rate, and (d) central safety factor, q(0), as measured by the motional-Stark-effect polarimeter. The arrow is at the time of peak $\beta_\alpha(0)$.

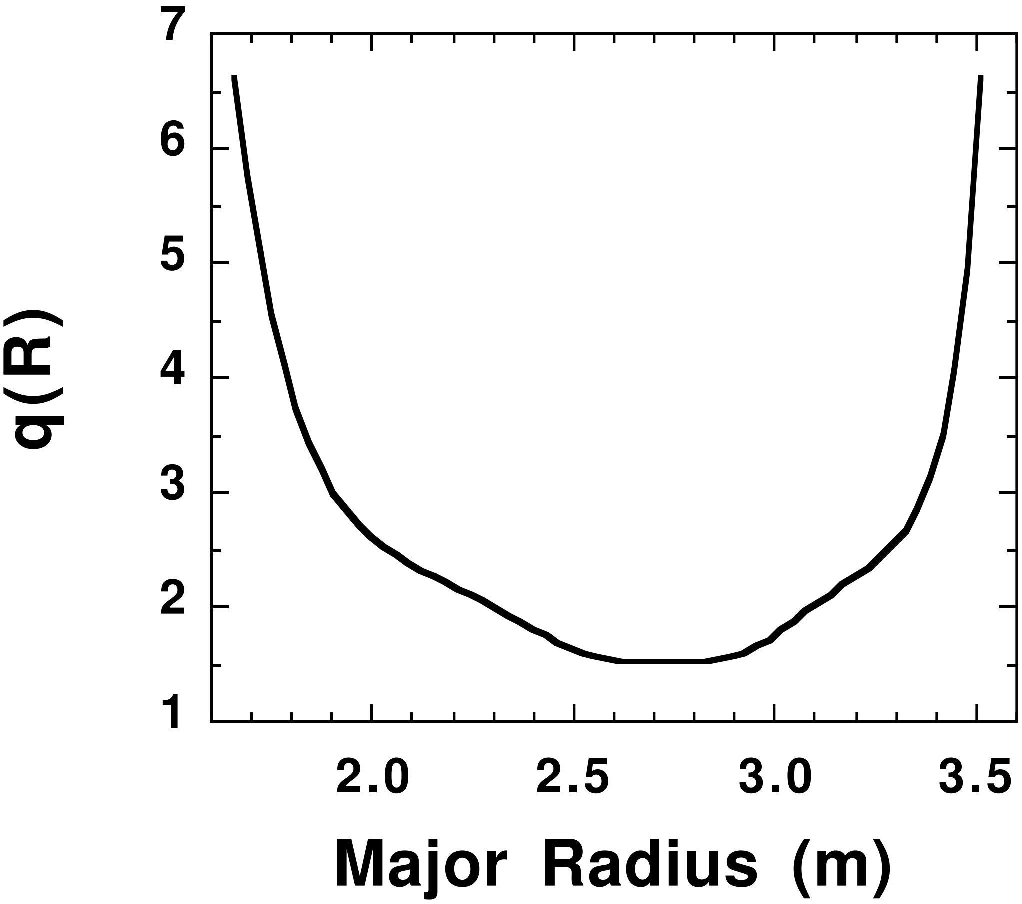

Fig. 2. The q profile at t = 4.36 sec, the time of peak $\beta_{\alpha}(0)$, from MSE measurements interpreted by the VMEC equilibrium code.

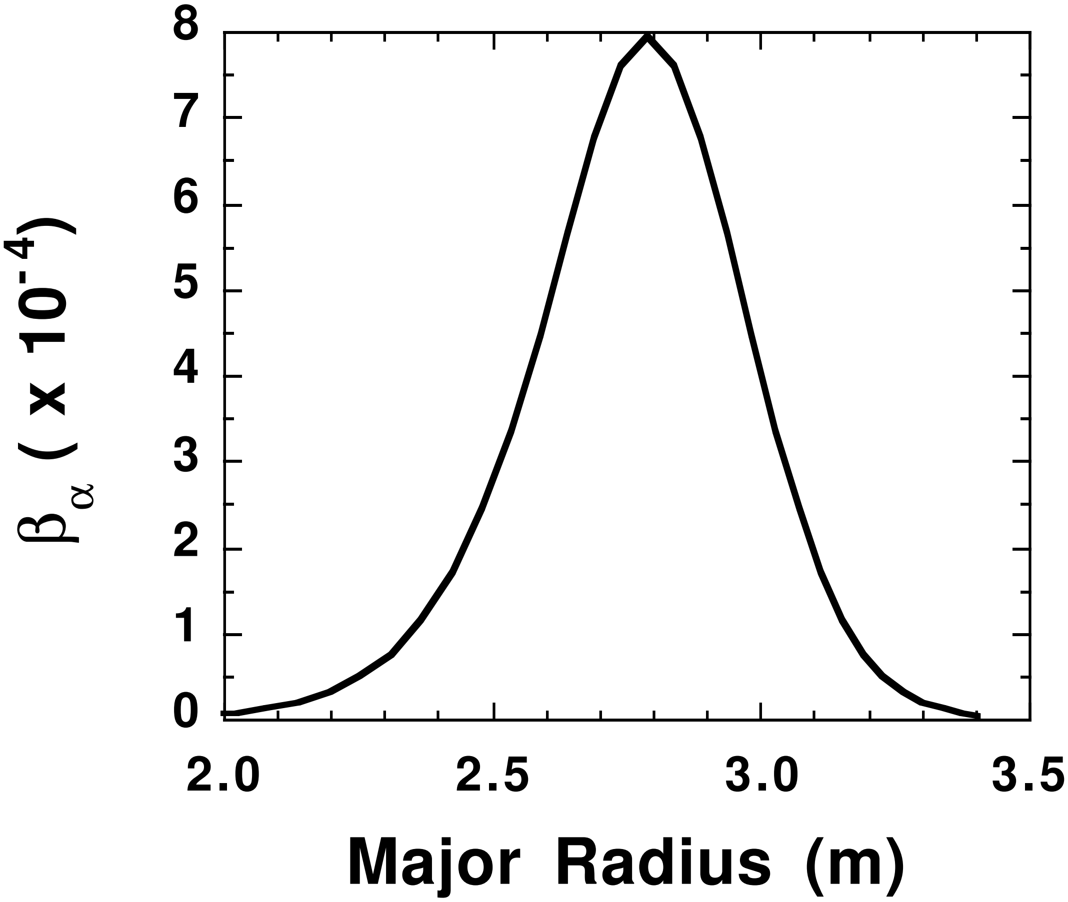

Fig. 3. The β_α profile along the tokamak equator at time of peak $\beta_\alpha(0)$ from TRANSP.

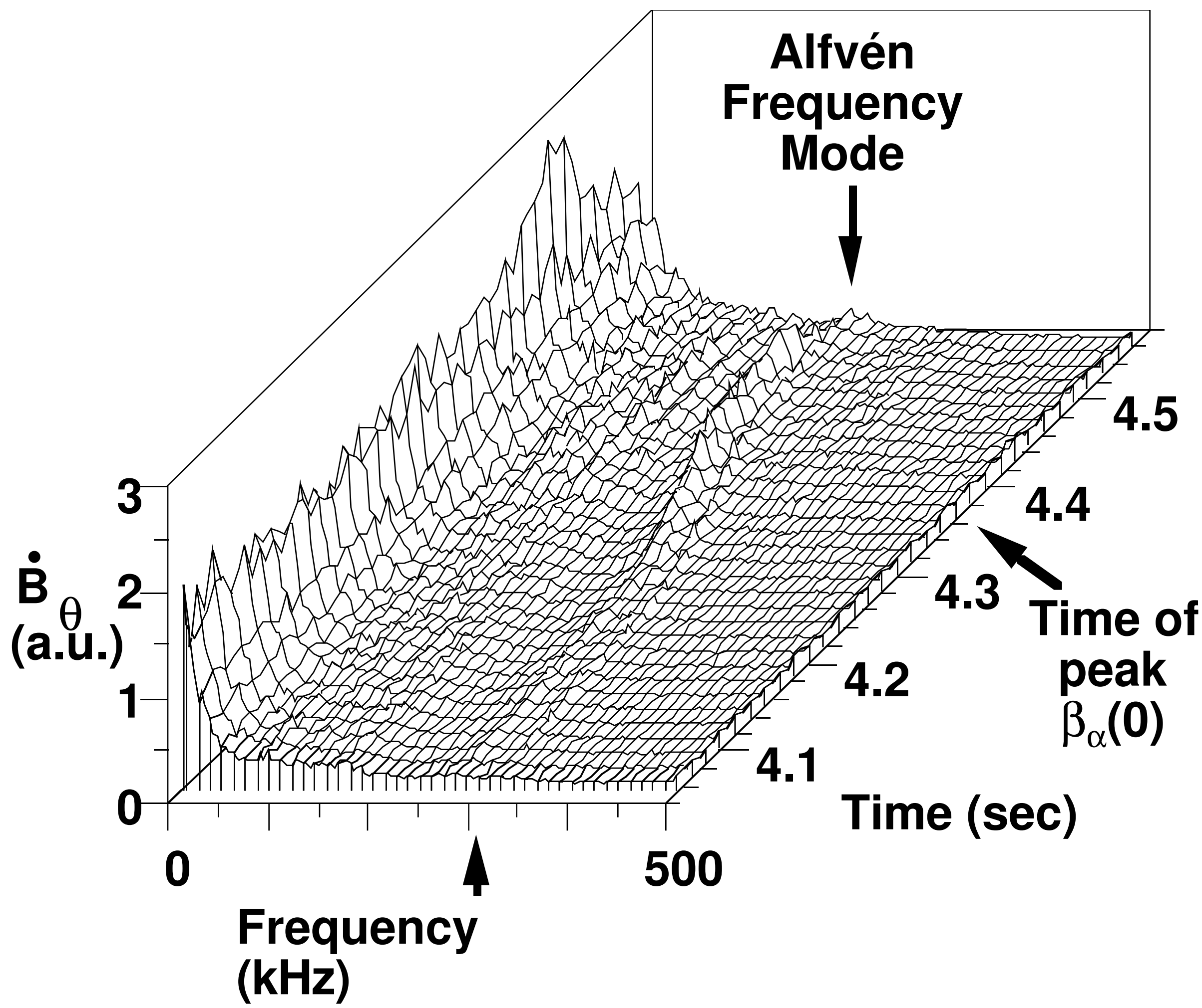

Fig. 4. MHD activity measured by the Mirnov coil array during the main heating phase of the discharge shows the usual Alfvén Frequency Mode which is not an alpha-particle-driven TAE.

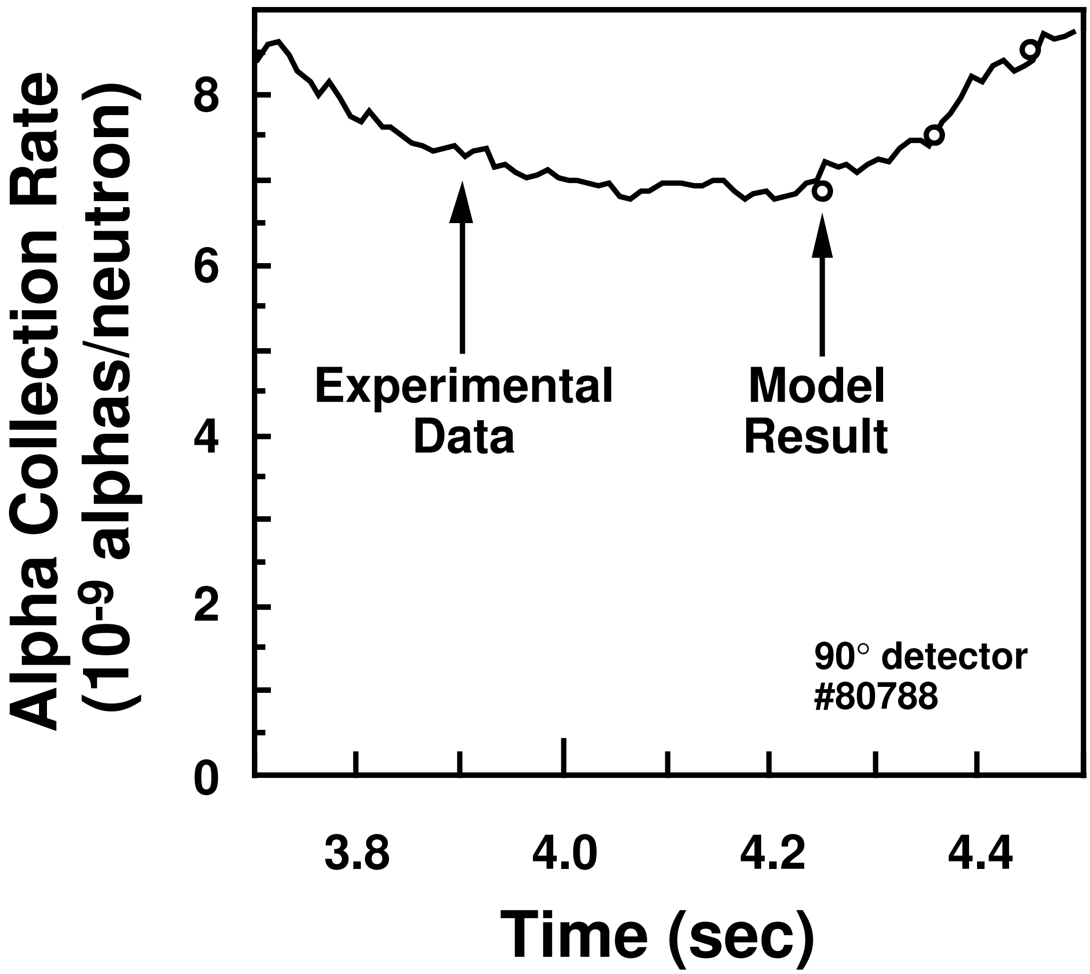

Fig. 5. Loss rate of alpha particles from the plasma measured 90° below the plasma equator. Also shown are calculations from the ORBIT code. The measurement is normalized to the code calculation at t = 4.36 sec.

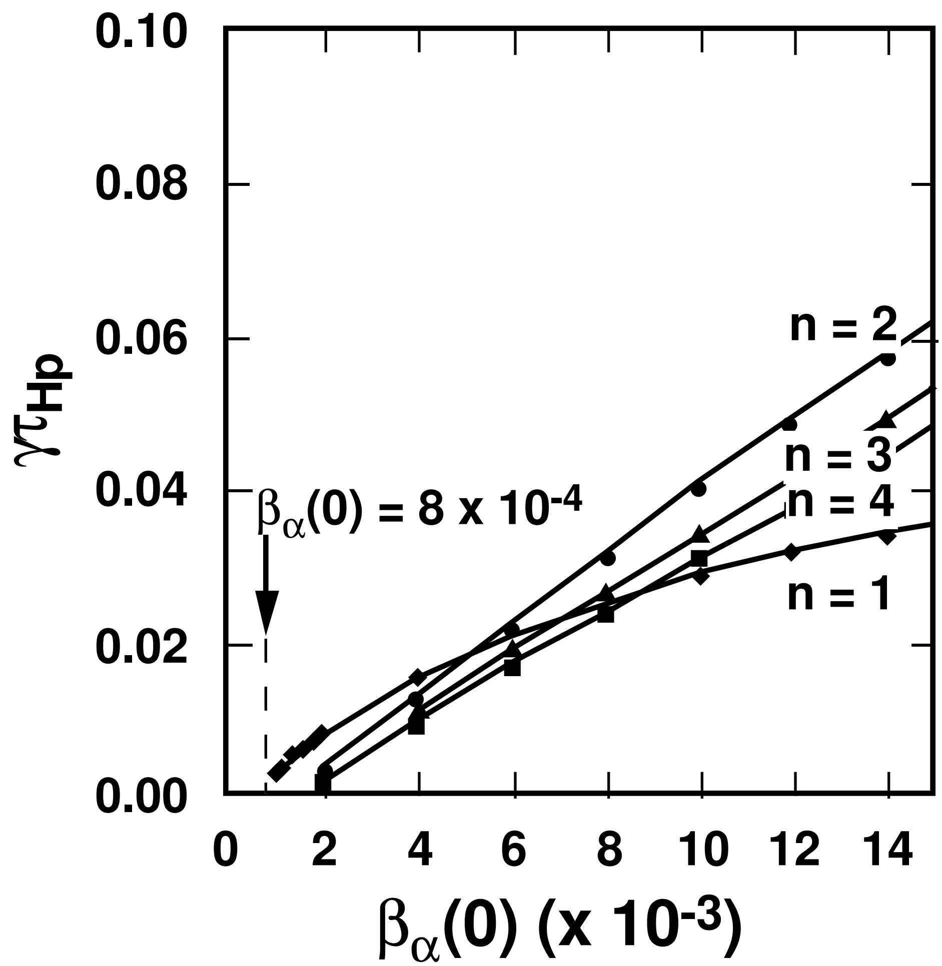

Fig. 6. TAE mode growth rates calculated by the gyrofluid code as a function of the central β_α for discharge 80788 at time of peak β_α . The achieved β_α was below the threshold for TAE excitation. Here $\tau_{Hp} = R_{mag}/V_A(0)$ where $V_A(0)$ is the Alfvén velocity at the magnetic axis.

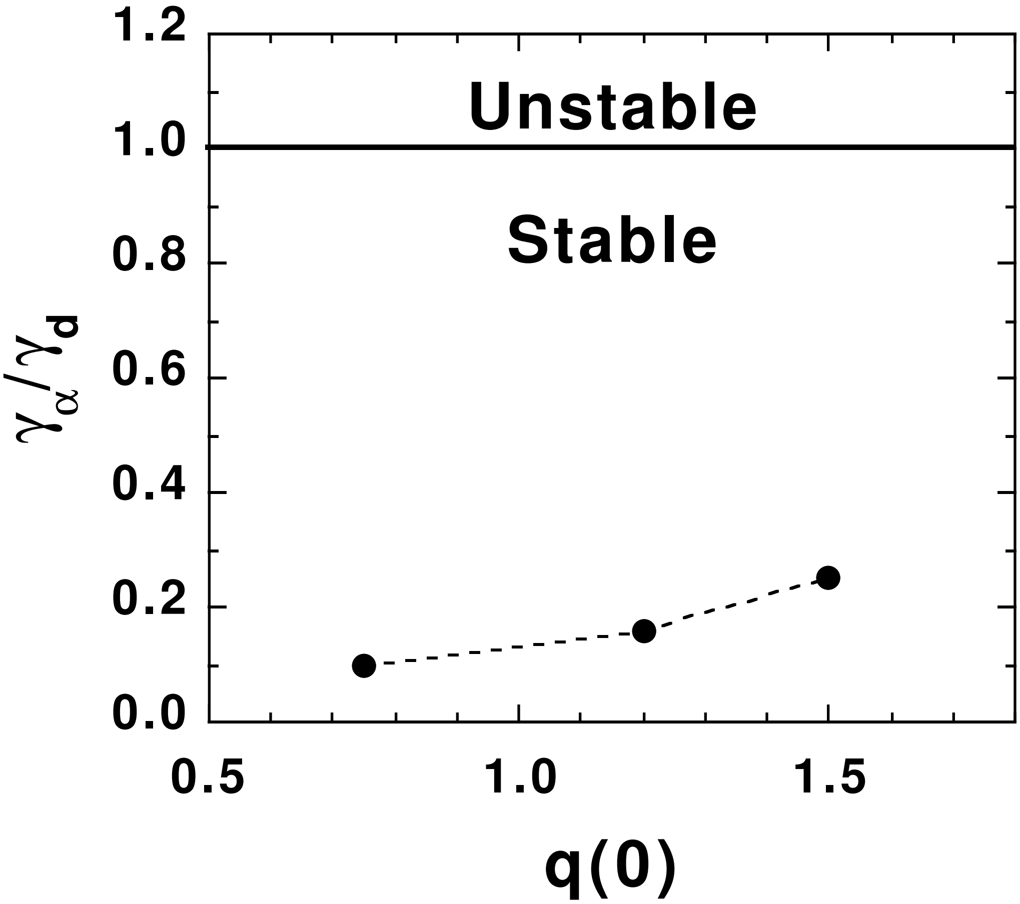

Fig. 7. TAE stability threshold for the most unstable toroidal mode, n = 3, as calculated by the NOVA-K code. Here, γ_α and γ_d are the TAE growth and damping rates, respectively.