TAE MODES AND MHD ACTIVITY IN TFTR DT PLASMAS

BY

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Abstract

The high power deuterium and tritium experiments on TFTR have produced fusion α parameters similar to those expected on ITER. The achieved β_α/β and the $R\nabla\beta_\alpha$ in TFTR D-T shots are 1/2 to 1/3 those predicted in the ITER EDA. Studies of the initial TFTR D-T plasmas find no evidence that the presence of the fast fusion α population has affected the stability of MHD, with the possible exception of Toroidal Alfvén Eigenmodes (TAE's). The initial TFTR DT plasmas had MHD activity similar to that commonly seen in deuterium plasmas. Operation of TFTR at plasma currents of 2.0 - 2.5 MA has greatly reduced the deleterious effects of MHD commonly observed at lower currents. Even at these higher currents, the performance of TFTR is limited by β-limit disruptions. The effects of MHD on D-T fusion α's was similar to effects observed on other fusion products in D only plasmas.

(1) MHD Activity in the initial TFTR D-T plasmas

Low m and n (m/n = 2/1, 3/2, 1/1, etc.) coherent MHD modes have been observed in the initial D-T plasmas on TFTR. The amplitude, frequency of occurrence and effect on plasma performance are similar to those observed in comparison D-only plasmas. The saturated level of the MHD activity agrees well with the predictions of the neo-classical model of MHD modes[1]. However, the theoretical models of the MHD behavior do not, as yet, explain why the higher m's (3, 4 or 5) are more commonly observed than the (m,n) = (2,1). Modeling of the effect of MHD on confinement suggest that the MHD can be responsible for up to a 30% decrease in the energy confinement time in the worst cases[2], consistent with the degradations observed. In cases of weak MHD, typical of most of the higher current plasmas (Ip > 2.0 MA, $q_{sh} < 4$), the effect is usually less than 5%. The decrease in neutron rate is consistent with the changes in the equilibrium plasma. It does not appear necessary to assume anomalous losses of fast beam ions to explain this decrease. Enhanced losses of fusion α's, correlated with the presence of MHD, are observed in DT plasmas. The losses are similar to those previously reported for DD plasmas[3].

Fishbone and sawtooth activity have also been observed in D-T plasmas. At present there is no evidence that the fusion α's have affected the sawtooth or fishbone stability. There is a tendency for the fishbone activity to be stronger in D-T plasmas; however, that may be more correlated with the somewhat broader pressure profiles often found in D-T plasmas, as compared to D-only plasmas under similar conditions.

(2) The β limit and disruptions in D-T plasmas

The DT fusion power which TFTR can produce is limited by pressure driven instabilities which can cause major or minor disruptions. The disruptive β limit in D-only NBI heated plasmas and D-T NBI heated plasmas appears to be similar. The β limit follows approximately the dependence predicted in the Troyon formula. In Figure 1 is shown the time history of the normalized toroidal β [$\beta_n = a_p(m)\ B_T(\text{Tesla})\ \beta_{tor}\ /\ Ip(MA)$] for three D-T shots which include a major and minor disruption. In this set of data, as well as the broader data set including D-only operation, there is some variation in the β_n which can be reached before major or minor disruptions occur. The variations may be correlated with changes in the peakedness of the plasma pressure profile. Some of the variation might also be attributed to a slightly stronger dependence on minor radius than is predicted in the Troyon formalism.

The high β disruption in D-only or D-T plasmas appears to be the result of a combination of an n=1 internal kink coupled to an external kink mode and a toroidally and poloidally localized ballooning mode[4]. In Figure 2 is shown contour plots of the electron temperature as measured at a 500kHz digitizing rate by the two ECE grating polychromators separated by 126° in the toroidal direction. The simultaneous absence of the ballooning mode on one GPC, and its presence on the second clearly demonstrates the toroidal localization of the mode. The ratio of the frequency of the ballooning mode and the n=1 kink indicate that the ballooning mode has a toroidal wave number of about 10-15 (assuming only toroidal rotation). The kink mode can have a growth rate in excess of 10^4/sec. This growth rate is much faster than the Sweet-Parker or tearing mode growth rates, and slower than the ideal growth rate. The experimentally observed growth rates are in reasonable agreement with the growth rate for collisionless plasmas. Here the inertia of the plasma plays a more important role than the resistivity[5] and the growth rate is given approximately by $\gamma\tau_{\text{Alfvén}} = q'\rho_s/q$ or $\gamma \approx 3\text{x}10^4$/sec.

The radial structure of the kink mode suggests coupling of a predominantly internal kink to a weaker external kink. The profile of the radial displacement of the flux surface due to the kink (and the ballooning mode) for a D-T shot generating a peak fusion power >9MW is shown in Figure 3. For comparison is the radial displacement as predicted by the PEST stability code. While PEST predicts that the n=1 kink is unstable for this disrupting plasma, it also in general predicts that most supershot plasmas are similarly unstable, as q(0) is typically less than unity[6] and the plasma pressure is sufficient to drive an ideal mode.

The kink mode can locally decrease the magnetic shear and increase the local pressure gradient so that the ballooning mode is locally destabilized. The thermal quench phase may result from destruction of flux surfaces by the non-linear growth of the n=1 kink, possibly aided by the presence of the ballooning modes. There is no evidence for a global magnetic reconnection as is seen in high density disruptions. The electron temperature collapses on a time scale of several hundred µsec with no local flatspots, indicating that the magnetic geometry is destroyed uniformly over the the plasma cross-section. The thermal quench phase is typically preceded by a large non-thermal ECE burst. The burst is at least 10 to 20 times larger than is predicted by the fast compression of electrons by a rapidly growing internal kink displacement[7].

Minor disruptions are more commonly observed than major disruptions. The type of precursor activity and the parameter regime in which they appear are very similar to those for the major disruptions. While the minor disruptions do not result in termination of the discharge, they do result in strongly degraded performance, compromising the usefulness of such discharges for D-T physics studies. While the minor disruptions result in a central electron temperature drop and a burst of H_α emission from the plasma edge, they are not related to either sawteeth (which have a resistive precursor and a reconnection in the core) or ELM's (the H_α burst results from a transient deposition of plasma energy from the core, rather than the plasma edge, on the limiter). The minor disruptions can cause a transient burst of fusion product losses. Figure 4 shows the lost α detector signal from which it is estimated that 0.1% of the confined fast α's were lost in several hundred μsecs. The loss is smaller than in major disruptions, where up to 20% of the stored energy in the fast α population may be lost in several bursts spanning a few msec. This level and rate of α loss could cause severe damage to internal hardware in ITER.

Experiments to increase the fusion power yield are planned. These experiments will make use of an increase in the toroidal field by 10-15% to increase the maximum plasma stored energy at the present β limit[8]. Experiments are also proposed to increase the β limit through modifications of the current profile. Increasing the peakedness of the current profile (and decreasing the edge current density) has been demonstrated to increase the achievable β at otherwise fixed parameters[9]. The increased fusion power will increase the β_α, extending studies of α physics closer to normalized ITER α parameters.

(3) Toroidal Alfvén Eigenmodes studies

In ITER and future fusion reactors, the Toroidal Alfvén Eigenmode (TAE) activity may result in enhanced fusion α losses, causing decreased performance and endangering internal components. An important goal of the TFTR D-T experiments is to improve the theoretical understanding of Toroidal Alfvén Eigenmodes, resulting in a higher level of confidence in code simulations of TAE activity in ITER. Fluctuations in the TAE range of frequencies have been observed under many conditions on TFTR, including shots with NBI at low magnetic field, ICRF H-minority heated plasmas, supershots, L-mode plasmas and in ohmic shots with pellet injection. Figure 5 compares the observed frequency of magnetic fluctuations to a semi-empirical scaling relation for the expected TAE frequencies.

The toroidal Alfvén eigenmode is a natural resonance of the plasma for which the frequency is determined by the ratio of the plasma mass to the restoring force due to sheared displacement of the magnetic field. The modes are usually damped by several mechanisms including Landau damping on the electrons, beam ions and thermal ions. The modes are destabilized by a super-Alfvénic fast ion population.

An extensive series of experiments on TAE modes driven by fast ions from neutral beam injection[10] (NBI) at (B_T = 1-1.2 T) and ICRF heating of an H-minority species[11] (B_T = 3T) has been carried out on TFTR for the purposes of experimentally verifying the instability thresholds predicted by the theoretical models. The range of parameters covered by these experiments is indicated by the shaded regions shown in Figure 5. These experiments have been very useful in the bench marking and improvement of the codes which are used to predict α-driven TAE behavior in TFTR and ITER.

The TAE activity is primarily studied using the Mirnov coil system to measure the magnetic fluctuations at the plasma edge and the reflectometer for measurements of density fluctuations in the plasma interior. TAE modes have also been observed with the BES system and the ECE grating polychromator. The Mirnov system is used to measure the toroidal wave number of TAE modes and the reflectometer provides an internal measure of the TAE mode amplitude.

In experiments using ICRF H-minority heating to create a super-Alfvénic fast ion tail, a cluster of very narrow peaks in the frequency spectrum are typically observed. The separate peaks, corresponding to different toroidal mode numbers, n, are separated by 2 to 4 kHz. The measured n numbers range from as low as three in the low current ICRF plasmas to larger than 8 at higher plasma currents. Calculations of the mode frequency and stability with the NOVA-K code find reasonable agreement with the measured frequency. Figure 6 shows the magnetic fluctuation spectrum from an ICRF heated plasma with the experimentally determined toroidal mode numbers from the Mirnov coil array[12] and the theoretically calculated TAE frequencies marked. TAE modes have also been observed with 64 MHz ICRF H-minority heating at a toroidal field of 4.6 T. In these experiments, the Mirnov and reflectometer spectra tend to have just one or two strong peaks (Fig. 7). The toroidal mode number is found to increase with increasing plasma current, dropping from n=6 at 1.8MA to n=3 at 1.4MA.

The fast ion loss was measured and the level of loss was correlated with the measured amplitude of TAE activity over roughly two orders of magnitude[3]. These experiments used both ICRF tail and NBI fast ion driven TAE modes. The TAE-induced diffusion of a trapped fast ion population is suspected of being the source of ripple trapped ions responsible for the recently detected damage to the TFTR vacuum vessel.

(4) Toroidal Alfvén Eigenmodes in D-T plasmas

The highest fusion power shots on TFTR have produced fast α populations comparable with some dimensionless alpha parameters comparable to the projected fast α populations for ITER, e.g., $R\nabla\beta_\alpha$. In Figure 8 is shown the typical structure of a TAE mode, superimposed on the α pressure profile as calculated in TRANSP. The amplitudes of the TAE modes peak at large minor radius and are typically only weakly coupled to the fusion-α's. In typical TFTR D-T supershots the thermal and beam ion Landau damping are stronger than the fusion-α drive. Experiments were successfully done to reduce the thermal ion Landau damping; however, the α-drive was still not sufficient to overcome the beam ion Landau damping[13,14].

Experimentally the search for α-driven TAE activity in D-T plasmas is complicated by the presence of a mode near the expected TAE frequency in both D-D and D-T NBI heated plasmas. The mode has a relatively broad peak in frequency, with a spectral width of about 50kHz at 300kHz. The frequency of the NBI driven activity is found to approximately fit the semi-empirical scaling relation developed from the H-minority ICRF and low toroidal field (B_T = 1 Tesla) NBI driven TAE mode data (Fig. 5). A mode at similar frequency has also been observed near the plasma center with the reflectometer; it is not known at this time whether the modes are the same. The toroidal mode number found for this peak is n=0. Non-linear numerical simulations of TAE modes by Spong[15] have predicted that the interactions of multiple TAE modes would result in an n=0 mode. The modes may represent a 'thermal' level of excitation or be driven by fast beam ions. For these plasmas the beam ion velocity is one third to one fifth the Alfvén velocity.

In Figure 9 is shown the spectrum of the edge magnetic fluctuations for a D-T shot with 7.5MW of fusion power and for a similar shot at 6.5MW and a D-only shot. The mode amplitude has increased by a factor of 2-3 in the 7.5MW shot. The NOVA-K code[13] finds n=5 and n=6 core-localized modes in the region where q<1 in this plasma (Figure 10). The localization of the mode near the plasma core increases the coupling of the fusion α's which makes the mode unstable. The calculated TAE mode frequency from the NOVA code was about 250 kHz, lower than the experimental frequency of 300 kHz. In this experiment the toroidal mode number was not measured.

No fusion product loss mechanisms beyond those seen in DD have been observed in full power DT shots with S_n as high as 3.2×10^{18} neutrons/sec and

$P_\alpha \approx 1.8$ MW. Scintillator probes located at 90°, 60°, 45°, and 20° below the outer midplane detect alpha particle losses. The results from the 90° detector match the first orbit loss model in magnitude, Ip dependence and pitch angle distribution. For detectors closer to the midplane, the first orbit loss model does not adequately fit the losses from DD or DT plasmas. Collisional and stochastic toroidal field ripple losses are being investigated as a possible explanation of the pitch angle distributions observed there. The anomalous delayed loss seen for DD fusion products has not yet been seen for α particles. No evidence of α loss due to α -driven instabilities has yet been seen.

Summary

The high power deuterium and tritium experiments on TFTR have provided the first look at the effect on MHD activity of a fusion α population similar to that expected on ITER. In the TFTR DT experiments to date there is no evidence for α loss due to α-driven instabilities; however, one of the highest fusion power shots may have evidence of α-driven TAE activity. Theoretical calculations suggest that presently achieved α parameters in TFTR are close to the stability threshold for α-driven TAE modes. Low m MHD, fishbones and disruptions appear very much the same in D-only and DT plasmas. At the higher currents used in the DT experiments, the performance of TFTR is still limited by β-limit disruptions. Studies of the β-limiting disruptions with the extensive MHD diagnostics set has provided valuable information on the structure of the disruption precursors. In particular, TFTR has provided the first clear evidence of strong ballooning activity in high β_n plasmas. The enhanced loss of D-T fusion α's during MHD activity, e.g., (2,1) modes, is similar to that observed in D-only plasmas for other fusion products .

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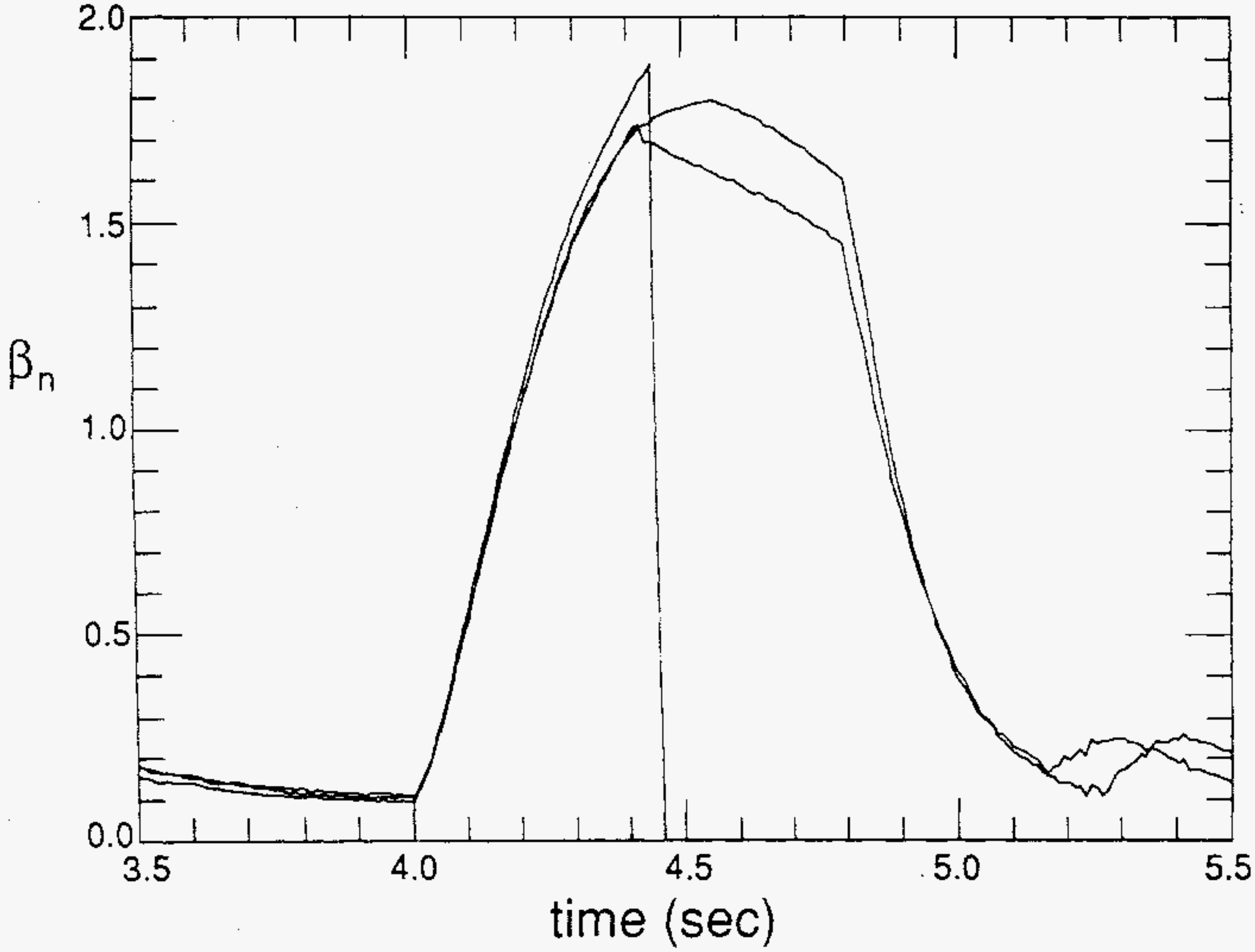

Figure 1 Time evolution of β_n for three of the highest fusion power D-T shots.

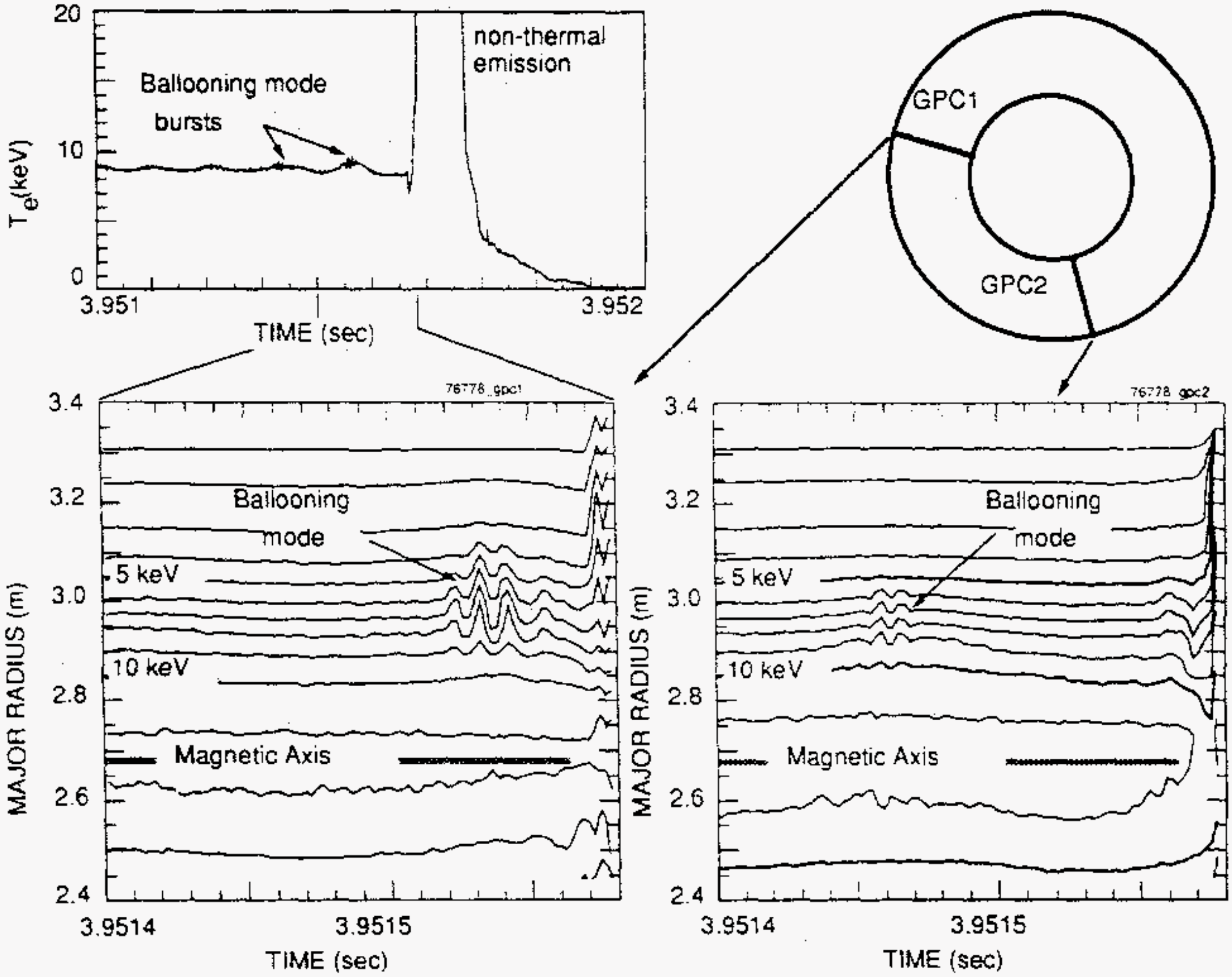

Figure 2 Contours of the electron temperature prior to a high β disruption showing the n=1 kink and ballooning precursors.

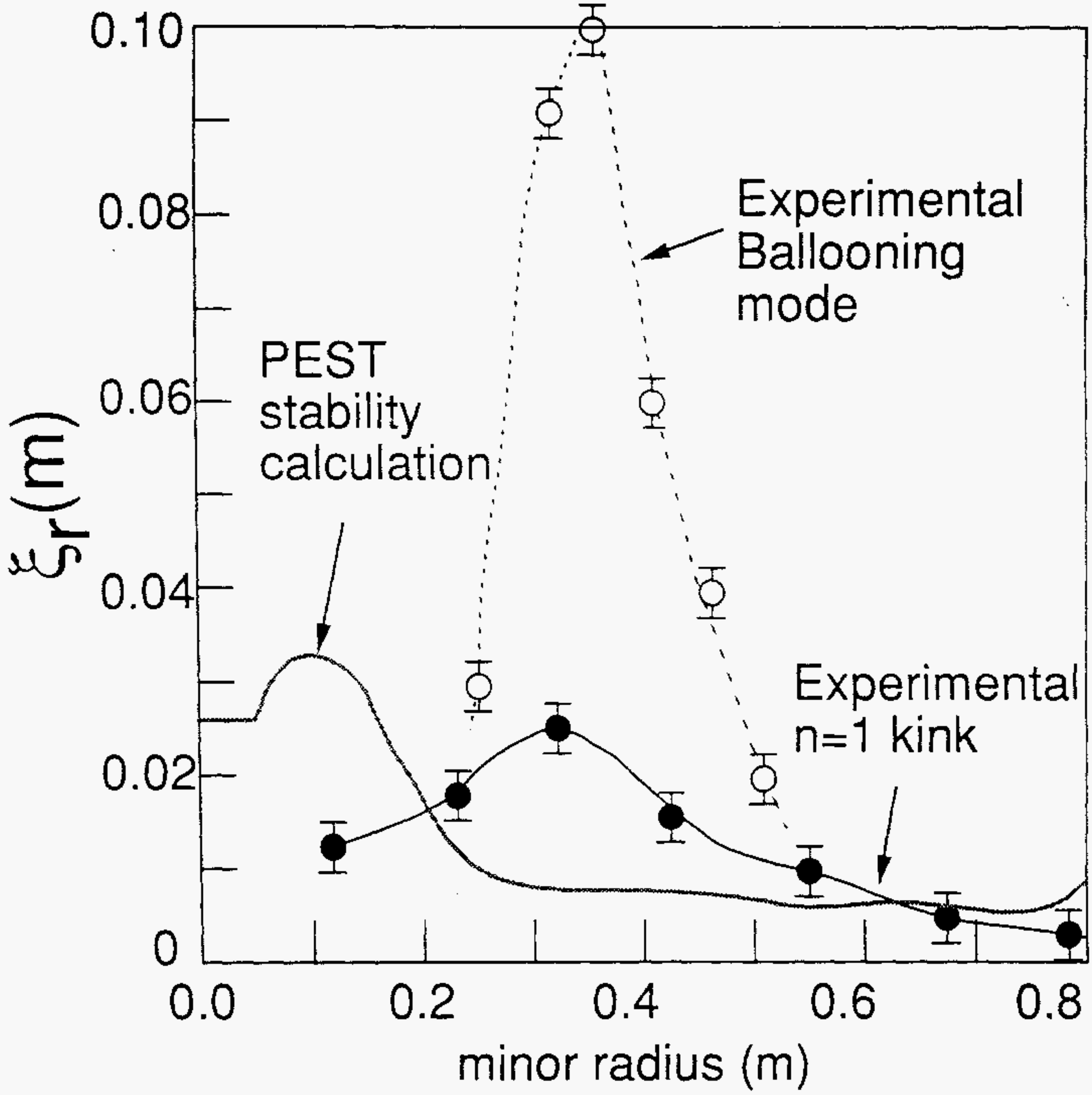

Figure 3 Radial profile of the radial displacement of the flux surface as determined experimentally and from the PEST code.

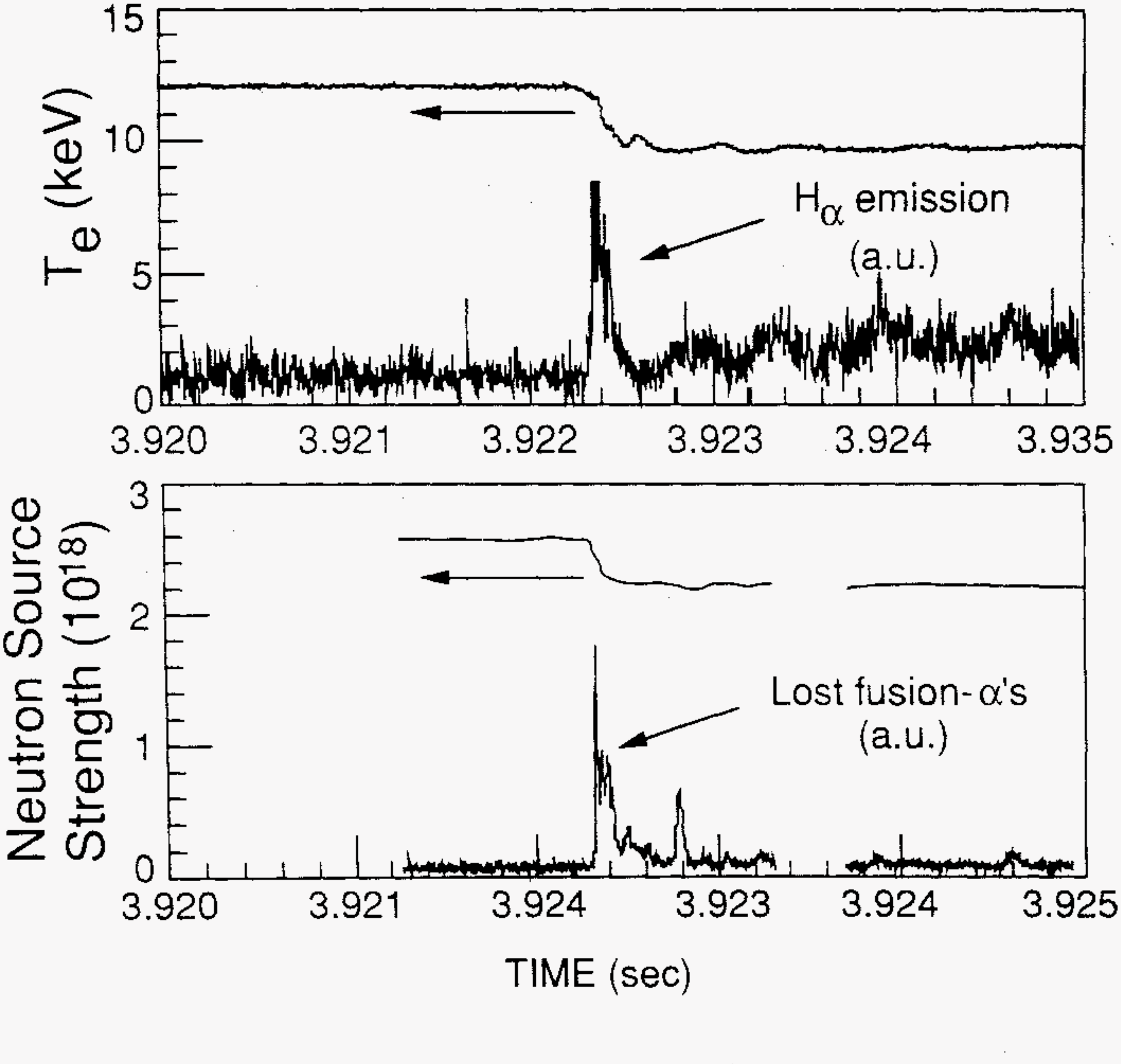

Figure 4 Central electron temperature, edge H_α, global neutron rate and alpha loss rate through a minor disruption.

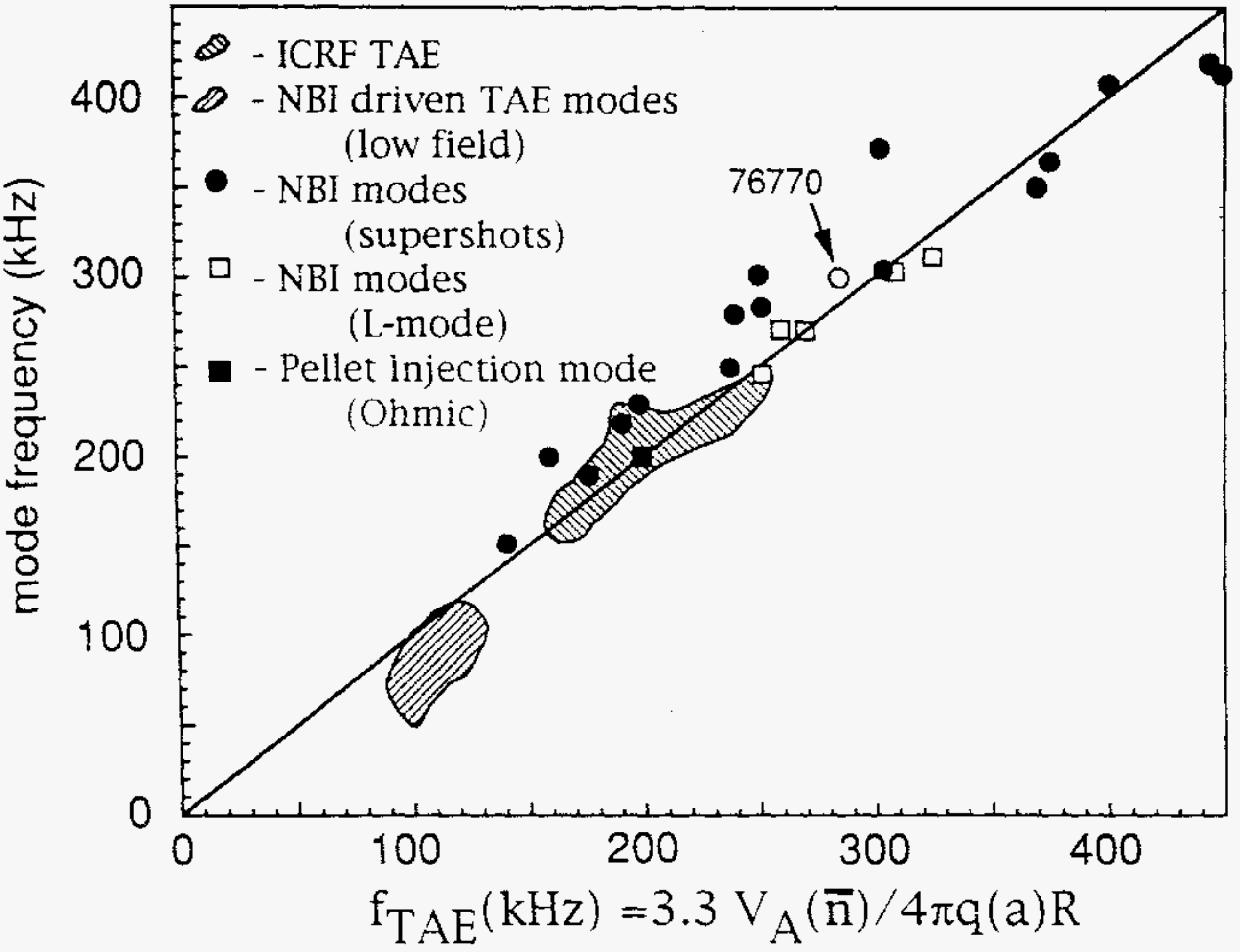

Figure 5 Scaling of theTAE activity frequency with a semi-empirical scaling relation.

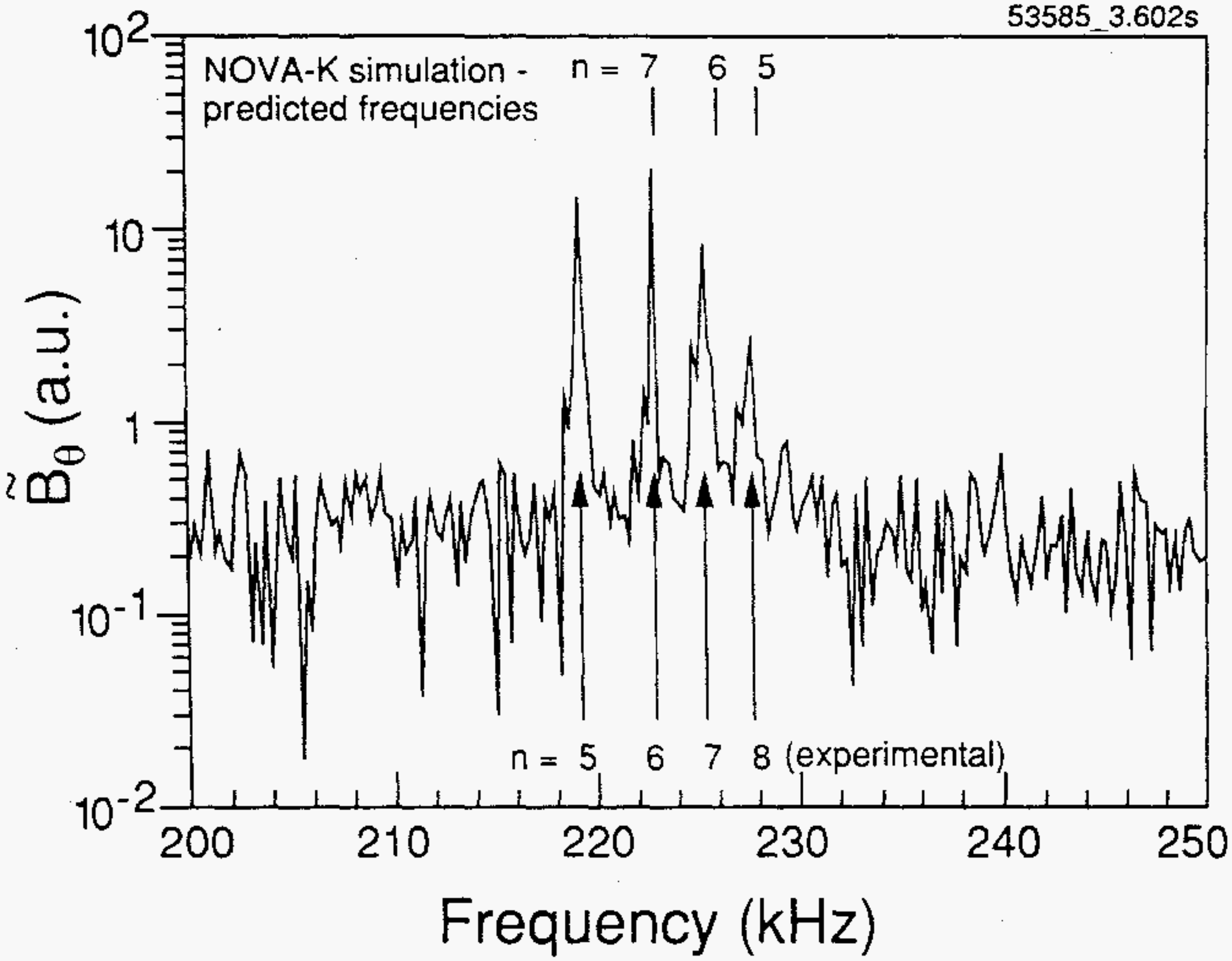

Figure 6 Comparison of the measured magnetic fluctuation spectrum and toroidal mode numbers to the NOVA-K predictions.

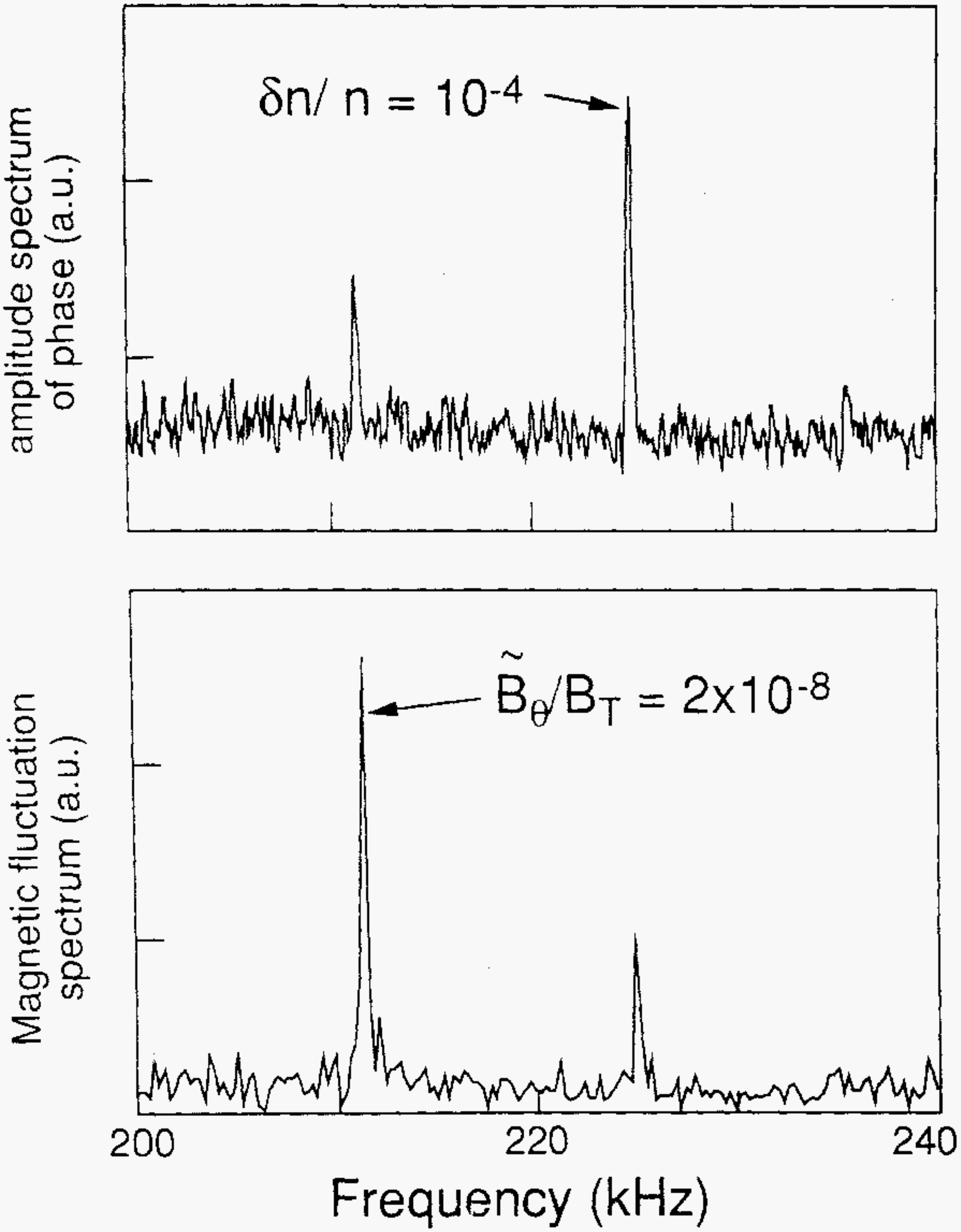

Figure 7 Reflectometer and Mirnov coil spectra for ICRF driven TAE mode.

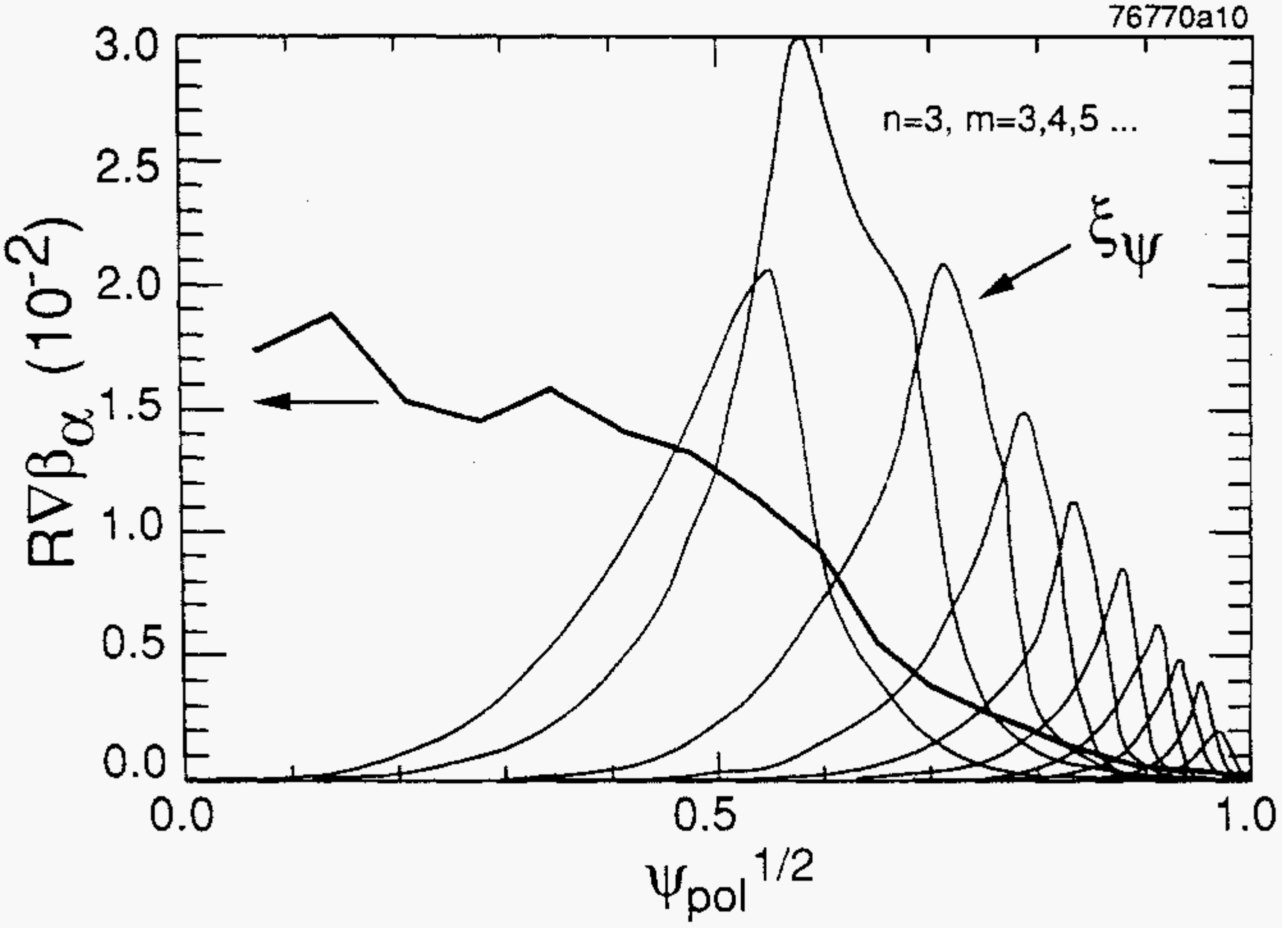

Figure 8 Typical TAE mode structure for a TFTR supershot superimposed on the calculated normalize α pressure gradient.

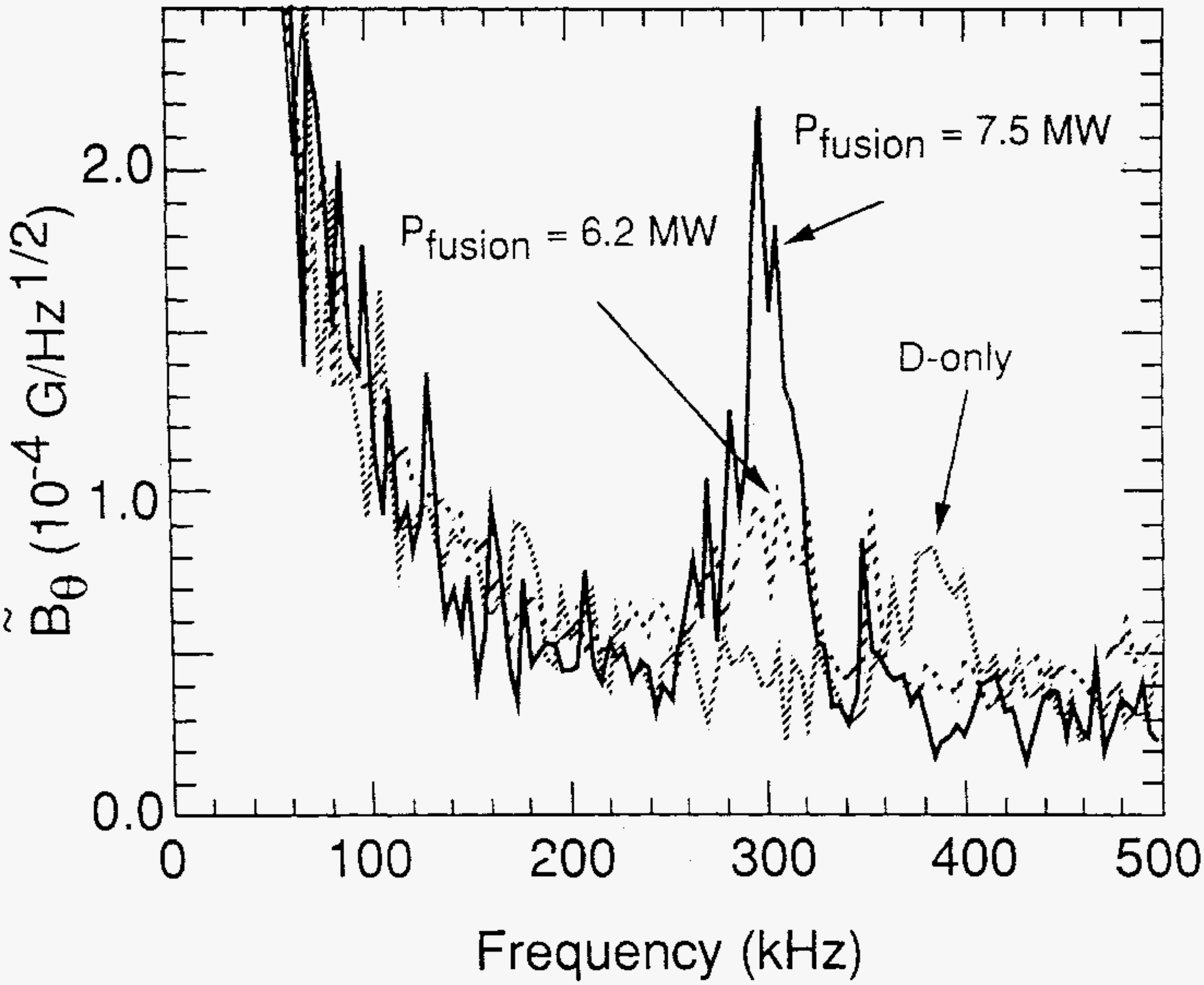

Figure 9 Spectrum of magnetic fluctuations for D-T plasmas generating 7.5MW and 6.2MW of fusion power and a D-only plasma.

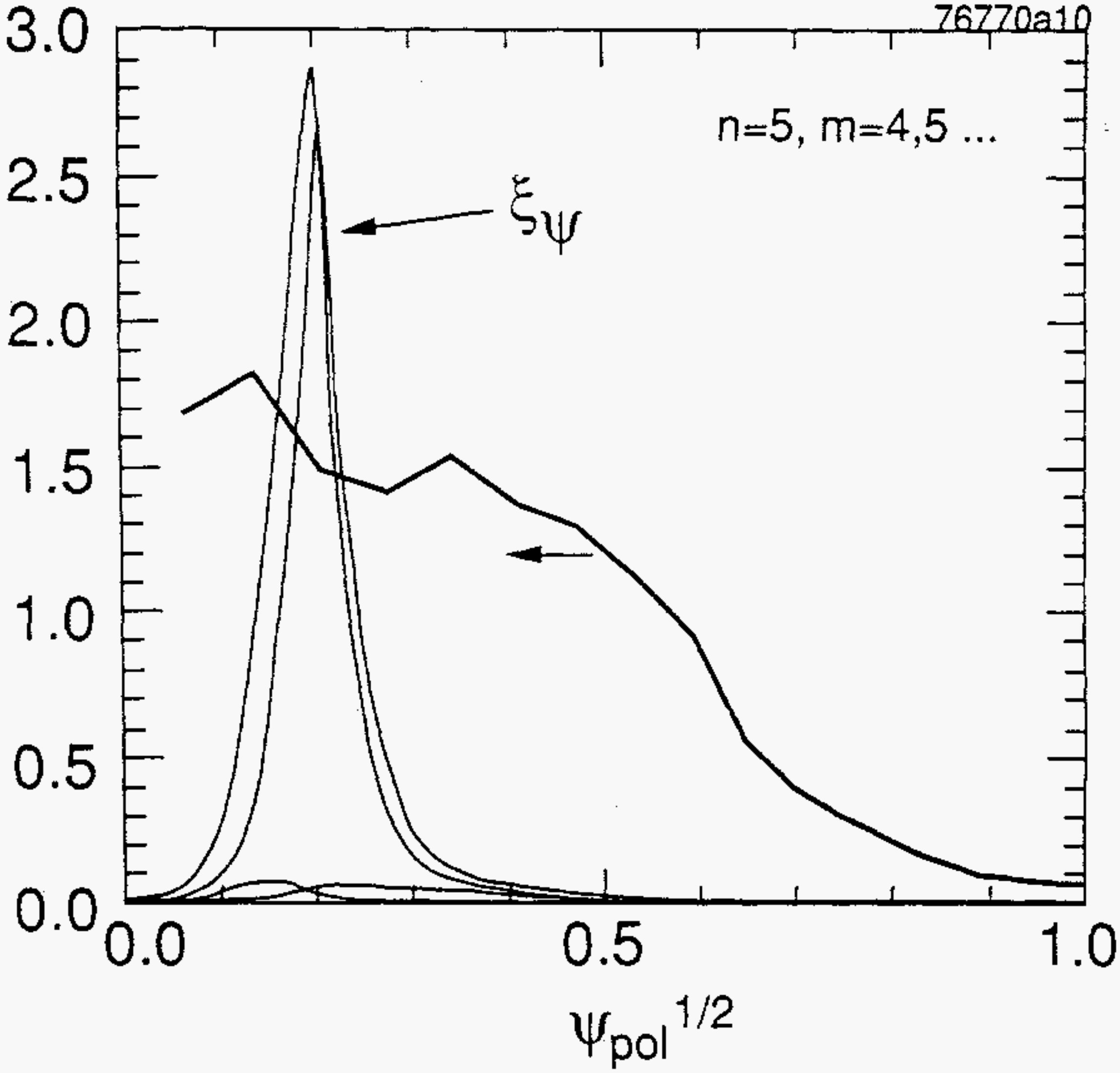

Figure 10 NOVA-K calculation of the mode structure for 7.5MW fusion power shot. Bold curve is the calculated normalized a-pressure gradient.

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