# Direct Measurement of TAE, EAE and Multiple Kinetic TAE in JET

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## 1. Introduction

A concern for tokamak reactors is that alpha particles, providing the main source of plasma heating, drive Alfven Eigenmodes (AE) unstable and in turn be subject to anomalous transport induced by these modes [1]. Experimental investigations into the AE linear stability properties and into the features determining their effects on particle orbits appear necessary.

## 2. The JET AE Active Diagnostic

To obtain this information a new AE active diagnostic has been developed at JET, combining excitation by external antennas with coherent detection of various probing signals, including the impedance of the driven saddle coils, the voltage on non excited saddle coils and magnetic coils, 8 ECE and 8 reflectometer signals [2]. The JET saddle coils are driven by a 3 kW amplifier in the range 30-300 kHz. The antenna currents (<30 A) generate low-n magnetic perturbations much smaller than those predicted to affect the particle transport significantly.

## 3. TAE and EAE Excitation and Identification

Many global AE have been driven in the frequency range from 50 kHz to 300 kHz and identified as Toroidicity or Ellipticity induced AE from their frequency dependence on density and magnetic field. The eigenmodes appear as resonances in the antenna/detector transfer function. The corresponding poles and residues provide the mode frequency, the total damping rate, $\gamma = \gamma_{damping} - \gamma_{drive}$, and the spatial structure. In Fig. 1 we see an example of a driven AE resonance, with the identification of the observed mode as a TAE being presented in Fig. 2.

## 4. Direct Measurement of TAE/EAE damping rates

Damping rates were measured in a wide variety of conditions, with $1\ \mathrm{MA} < I_p < 3\ \mathrm{MA}$, $1\mathrm{x}10^{19}\ \mathrm{m}^{-3} < \bar{n}_e < 5\mathrm{x}10^{19}\ \mathrm{m}^{-3}$ and $1\ \mathrm{T} < B_{tor} < 3.5\ \mathrm{T}$ [2]. The results with both odd and even low-n excitation span several orders of magnitude, from $\gamma/\omega < 0.1\%$ to $\gamma/\omega > 10\%$, suggesting that different absorption mechanisms dominate according to the configuration of each specific shot. Greatly differing damping rates were measured in similar discharges with different profiles of $g = 1/(q\rho^{1/2})$, the function determining the AE gap alignment and hence the significance of continuum damping (Fig. 3). With a strong radial dependence of g(r) (a), strong continuum damping occurred with $\gamma/\omega \sim 5\%$. g(r) in curve (b) was flatter and led to a more 'open' gap structure with much less damping.

## 5. AE spectrum in heated plasmas: kinetic AE

AE experiments have also been undertaken in additionally heated plasmas, to extend the parameter range for the damping measurements, to assess the driving effects of resonant fast particles and to study the AE spectrum in the presence of non-ideal MHD effects. A sudden change was observed in the spectra as $T_e$, $T_i$, $T_e/T_i$ and the magnetic shear were increased by means of high current ohmic heating, NBI, Lower Hybrid Heating (LHH), ICRH, or fast plasma current ramps. This transition appeared clearly in high current ohmically heated plasmas (Fig. 4). The single peak TAE observed for low $I_p$ is transformed into a multiple structure of less damped peaks at higher $I_p$, corresponding to a hotter plasma. As these modes are externally driven with $|n|=2$, with negligible plasma rotation, they cannot correspond to Doppler shifted peaks of different n. Similarly, multiple resonances with the same toroidal mode number characterised the spectrum of driven magnetic and density perturbations in the TAE range with LHH and moderate ICRH (Fig. 5). This first observation of driven density perturbations emphasises the non-ideal MHD character of the modes. Comparable spectra in the TAE/EAE gap frequency range, with similar peak frequency spacing, resonance width and mode numbers, have been driven during discharges with other additional heating methods. In most cases the observed structures consisted of several resonances with regular frequency spacing and damping rates significantly lower than for the corresponding 'cold' TAE. As they appear in experimental conditions which correspond to the predicted departure from ideal MHD behaviour due to kinetic effects, the observed modes are identified as kinetic AE [4].

## 6. Excitation of AE by non-linear beating of ICRH waves

The excitation of AE by ICRH beat waves was investigated experimentally. The frequencies of two different ICRH modules were mixed together to produce a beat wave signal at $\Delta f$, then used as the reference of the AE synchronous detectors. TAE were excited when $\Delta f$ coincided with the TAE gap centre frequency (Fig. 6). The relatively large amplitudes for the TAE driven by ICRH beat waves suggest that this non-linear excitation method could allow investigations into the effects of AE on particle orbits and should be taken into account in ICRH heated thermonuclear plasmas.

## 7. Conclusions

The successful implementation of a new active diagnostic for AE has allowed us to drive TAE and EAE in linearly stable conditions and to measure, for the first time, their damping rates in a variety of plasma conditions. Weakly damped, multiple kinetic AE have been excited and detected in the TAE/EAE gap frequency range on the JET heated plasmas. Resonant excitation of TAE by ICRH beat waves has also been demonstrated experimentally. The combination of these linear and non-linear studies should provide insight into the AE stability and their effects on alpha particles' dynamics in future ignition experiments.

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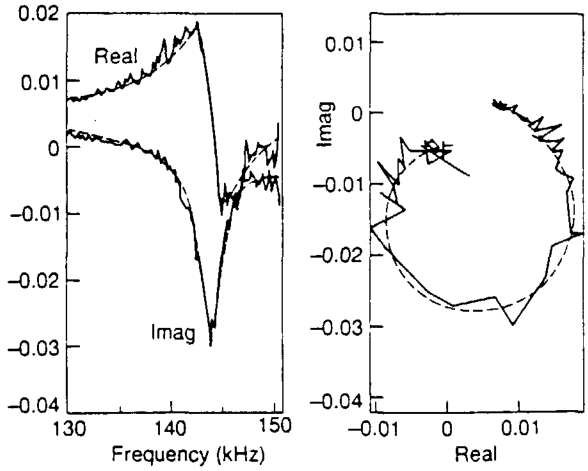
## References

[1] C.Z.Cheng, L.Chen, M.S.Chance, *Annals of Physics* **161**, 21 (1985).
[2] A.Fasoli et al., *Phys. Rev. Lett.*, in press (1995).
[3] D.J.Sigmar, C.T.Hsu, R.White and C.Z.Cheng, *Phys. Fluids B* **4**, 1506 (1992).
[4] R.R.Mett and S.M.Mahajan, *Phys. Fluids B* **4**, 2885 (1992).



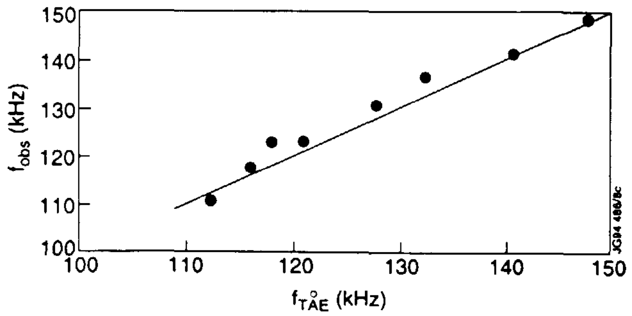


**Fig. 2** Measured eigenfrequency vs $f_{TAE}^0=v_A/2\pi qR$, the TAE gap centre, calculated for q=1.5 (#31591). $B_{tor}$ was varied linearly between 2.2 and 3 T.

**Fig. 1** TAE resonance in ohmic plasma (#31638). Real and imaginary parts (left) and complex plane representation (right) of a magnetic probe signal, normalised to the driving current. A fit with a transfer function of order 5/2 is shown, giving $f_{obs}=144.2$ +-0.1 kHz, $\gamma/2\pi=1400$ +-100 $s^{-1}$, $\gamma/\omega \cong 1\%$.

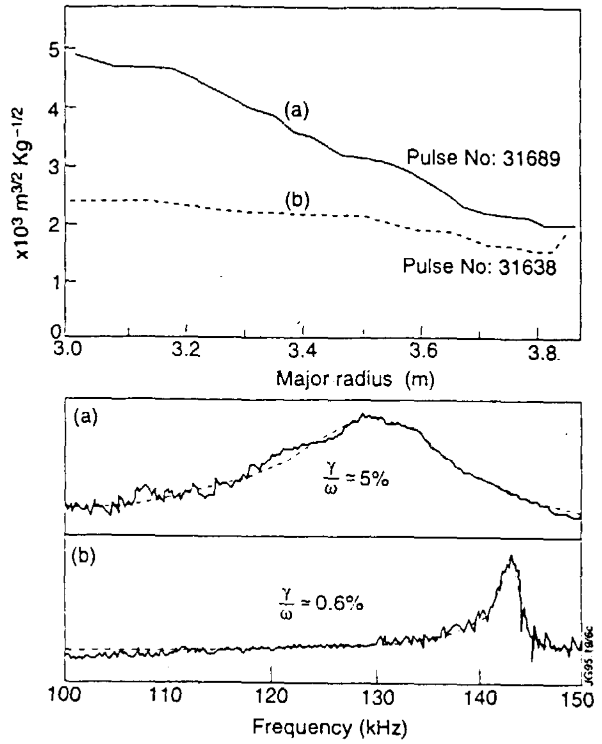


**Fig. 3** The relationship between the profile of $g(r)=1/(q(r)\rho(r)^{1/2})$ and the TAE damping. Excitation peaked at $|n|=2$ was used for both discharges; ohmic plasma, with $\bar{n}_e \cong 4\mathrm{x}10^{19}$ $m^{-3}$; (a) $B_{tor} \cong 1.8$ T. (b) $B_{tor} \cong 2.8$ T.

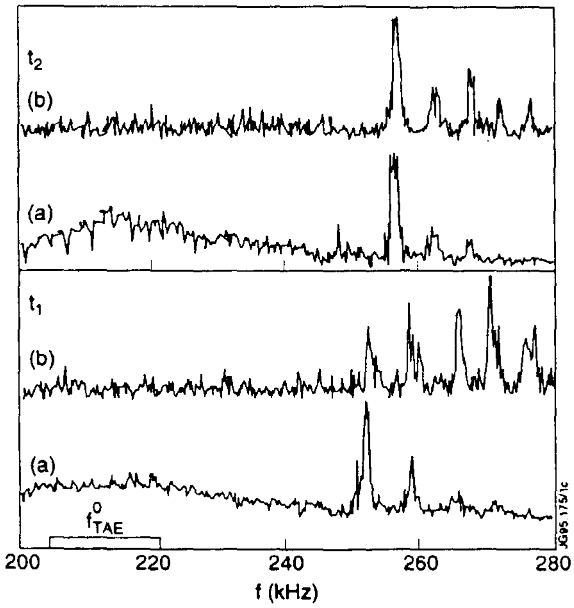


**Fig. 5** Spectrum of magnetic (a) and density perturbations at r/a~0.5 (b), with LHH (2.5 MW) and ICRH (6 MW). Two successive scans in shot #33157, at $t_1$ = 19 s and $t_2$ = 20 s, are shown. $I_p \sim 3$ MA; $B_{tor} \sim 3.2$ T; $T_e \sim 6.3$ keV; $T_i \sim 2.9$ keV.

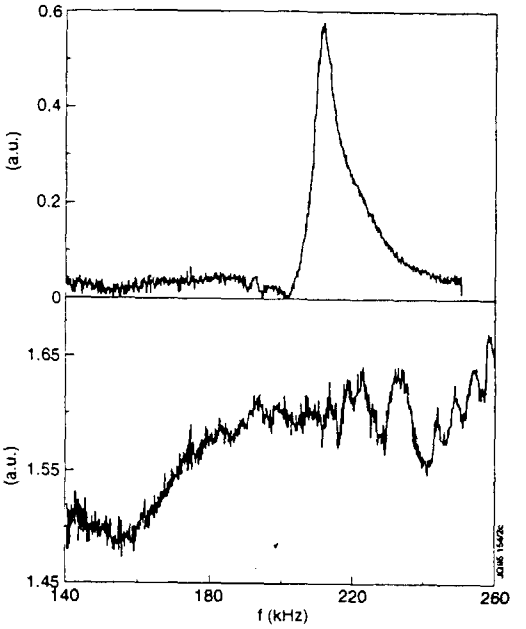


**Fig. 4** $\delta B_{pol}$ probe signals for moderate (top: t=3.5 s; $I_p$ ~2 MA; $B_{tor}$~2.5 T; $T_e$ ~2.2 keV; $f_{TAE}^0$~200 kHz) and high plasma current (bottom: t=9.5 s; $I_p$ ~ 4.1 MA; $B_{tor}$~2.9 T; $T_e$~3.2 keV; $f_{TAE}^0$~180 kHz) in shot #34073.

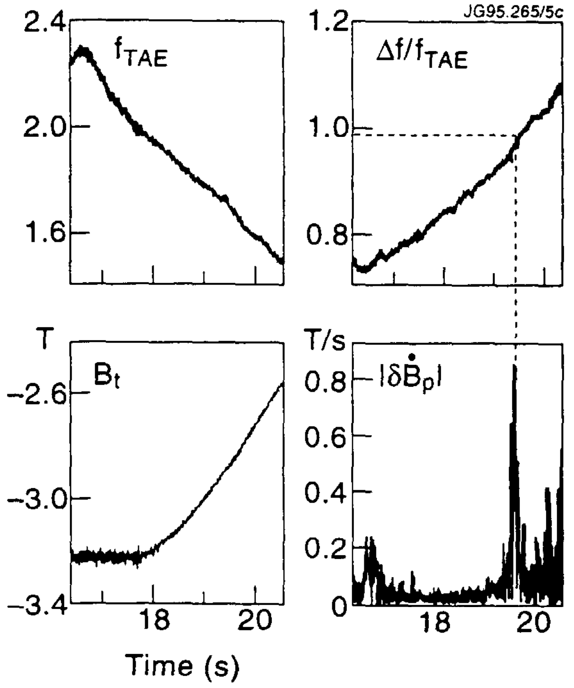


**Fig. 6** Observation of TAE driven by ICRH beat waves in shot #35051. Each module is in dipole configuration for hydrogen minority heating, with $f_{1,2} \sim 43$ MHz, and coupled power ~1MW; $I_p \sim 3$ MA; $T_e \sim 5$ keV.