Observation of TAE Activity in JET

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ABSTRACT
Recent analysis has revealed mhd activity in JET showing features of toroidicity-induced Alfvén eigenmodes (TAEs), in both ICRF heated and neutral beam heated plasmas. The mode frequency is found to scale in the expected way with the magnetic field and plasma density. The frequency spectra show the characteristic multi-mode TAE structures seen in other devices. Analysis of these indicates the presence of bi-directional propagating TAEs , as expected for Alfvén waves in general. In one case this appears to produce a standing TAE mode in the plasma frame. A correlation between fast particle losses and the mode amplitude is also suggested by the data.

1. INTRODUCTION
Toroidicity induced Alfvén Eigenmodes (TAEs) can be driven unstable by fast particles originating from neutral beam injection, ICRF heating or fusion reactions [1-4].

Their potential role in fusion reactors is a subject of concern, as they may lead to anomalously rapid losses of the fast α-particles, thereby reducing α-particle heating and possibly damaging the first wall.

TAEs have been observed in DIII-D and TFTR [5-8] with auxiliary heating, with associated losses of fast particles from the bulk plasma.

Theory predicts that the TAE frequency scales with Alfvén speed according to the formula $f_{TAE} \sim v_A / 4\pi qR$, where $v_A = B / \sqrt{\mu_0 \rho}$ is the Alfvén speed, at the surface of instability q, and R is the major radius.

Since the modes are driven by the pressure gradient of energetic particles, the most likely region for instability lies in the range $q \sim 1-2$, with typical mode numbers $n \leq 5$, and with the possibility of several modes being simultaneously unstable, as has been observed [7, 8].

For passing particles two resonances are predicted, when $v_{parallel} = v_A$ and when $v_{parallel} = v_A/3$ [1], whereas for trapped particles resonance requires the mode frequency to match either the banana orbit precession frequency or the particle bounce frequency, giving the criteria $v = v_A/(2qk_\theta\rho)$, and $v = (v_A / 2)\sqrt{R/r}$ respectively, where k_θ is the poloidal wave number and ρ is the energetic ion Larmor radius [4].

2. TAE DIAGNOSIS

TAEs are distinguished from other modes by

- their Alfvénic frequency scaling ($f_{TAE} \sim v_A / 4\pi qR$, $v_A = B / \sqrt{\mu_0\rho}$)
- their high frequency where the only other modes observed in JET are those identified with ELMs:

Activity type	Typical frequency in JET
Tearing/ kink modes	<50kHz
Fishbone-like	<30kHz
ELM precursors	>50kHz
TAE predictions	~100-200kHz

- the structure of their frequency spectra. It is predicted that several modes can be simultaneously unstable. This is observed in other experiments [5-8], where several closely spaced lines are resolved in the mode structure, characterising the TAE.
- the prediction of forward and backward waves (as for all Alfvén modes). First evidence for this is reported here, with implications for the interpretation of the frequency spectra.

The principle diagnostics suited for the study of these modes in JET are

- the magnetic diagnostic:

  System bandwidth <250kHz
  Max. acquisition rate=250kHz
  Band-pass filters covering 0-125kHz range available (rms data)

→ Acquire data without anti-aliasing filters and combine with band-pass filter data to determine mode frequency unambiguously in the 0-250kHz range

- the reflectometer:

  System bandwidth=100kHz

→ Observe lower end of TAE frequency range

3. JET AUXILIARY HEATING WHICH MIGHT EXCITE TAES

- Neutral beam heating: 140keV deuterium injection

→ Sufficient speed to excite $v_{parallel} = v_A / 3$ resonance in some low field plasmas

- ICRF heating: 1MeV protons, ^{3}He nuclei

→ Trapped particles unlikely to excite the main banana orbit precession resonance $v = v_A / (2qk_\theta\rho)$, but particle bounce resonance $v = (v_A / 2)\sqrt{R/r}$ can be excited. Passing particle fraction has adequate energy to excite both $v_{parallel} = v_A$ and $v_{parallel} = v_A / 3$ resonances.

4. JET DATA

An example of the mode is given in fig. 1 below. For a case with B=1.5T and P_{in}=4MW.

- The evolution of the envelope of the mode shows no correlation with the ELMs.
- This pulse contains 140keV deuterium injection alone, so that $v_D = 4 \times 10^6 m/s$ and the Alfvén speed is $v_A \sim 6 \times 10^6 m/s$.

→ $v_{parallel} = v_A / 3$ resonance should be excited.

- The predicted TAE frequency is within 10% of the observed frequency in this case.

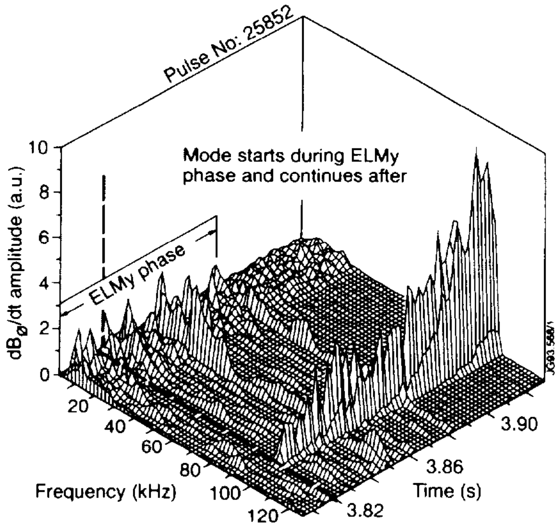

Fig. 1: A high frequency coherent mode in JET, measured by the magnetic diagnostic. The mode appears to be unrelated to the ELMs, and its frequency agrees with the calculated TAE frequency to within 10%.

The dispersion relation for TAEs gives two solutions for the frequency, with equal magnitude but opposite sign, in the plasma frame [e.g. 9], as for all Alfvén waves. This implies the existence of waves travelling in opposite directions. Plasma rotation doppler shifts these frequencies so that rotation in the 'forward' direction blue-shifts the forward wave, and red-shifts the backward wave.

→ For given (m,n) there may be two lines in the spectrum, a doppler shift above and below the TAE frequency.

Evidence in JET supporting this is given in fig. 2. This shows reflectometry data for the pulse in fig. 1.

- The mode has two branches and the frequency of these is seen to vary symmetrically about 92kHz.

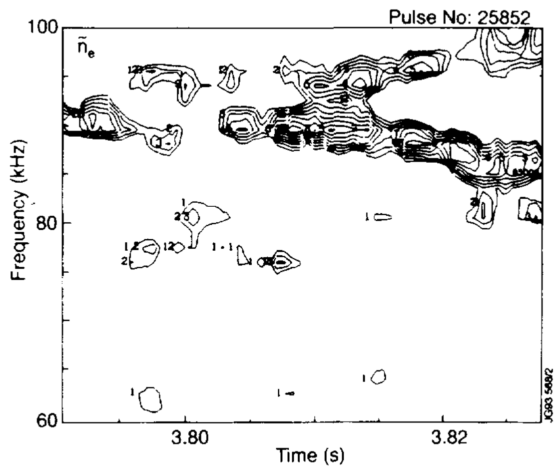

Fig. 2: Density fluctuations from reflectometry showing symmetric frequency variation of two branches, which can be understood as a result of varying plasma rotation, with bi-directional travelling TAE modes of the same mode number. The amplitudes of the two branches are not equal.

- We explain this as the doppler shift of a forward and backward TAE mode with varying plasma rotation.
- Note that the two branches do not have equal amplitudes. This is likely to be due to an asymmetric fast particle distribution.

An example of the TAE spectra from two pulses is given in fig. 3. The first is with 4MW neutral beam injection and 5MW ICRH input, and the second with 8MW ICRH alone.

- These spectra show several closely spaced lines as expected for TAEs.
- Toroidal mode numbers are typically $n \leq 6$ and adjacent lines differ by $\delta n = 1\text{-}2$.
- The separation of the lines is comparable to the central toroidal rotation of 5kHz, consistent with the cause being a doppler shift from plasma rotation.
- The spectrum of pulse 25938 is strikingly symmetric. This is expected in the case where

◊ the forward and backward waves have equal amplitude (i.e. the TAE driving term is symmetric)

and

◊ all the modes are unstable on q-surfaces close together (i.e. variation in TAE frequency is small compared with the doppler shift)

In this case, the TAE is a standing wave in the plasma frame and it is the lowest mode numbers that have the largest amplitude. Note that the TAE frequency is then the frequency at the *centre* of the structure. Usually the spectra are not so symmetric, and are more like that in pulse 25937 shown in fig. 3, so that the above conditions are not satisfied in general.

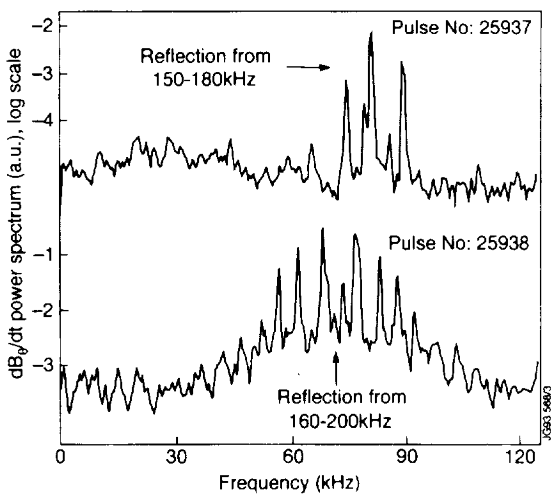

Fig. 3: Magnetic fluctuation spectra showing the simultaneous presence of several lines. A set of band-pass filters covering the 0-125kHz range show that the structures are aliased.

The data in fig. 3 are acquired without anti-aliasing filters to extend the bandwidth of observation. The sampling frequency is 250kHz. Consequently modes at frequency $f_{mode} = 125\text{kHz} + \delta f$ appear aliased at frequency $f_{alias} = 125\text{kHz} - \delta f$. Band-pass filtered data covering the 0-125kHz range are available, and can be used to determine the frequency uniquely. An example is given below in fig. 4. In pulse 25938 the mode seen in the spectrum of fig. 3 (at ~8.7s) should be detected on the 83kHz and 95kHz filters, and not on the 121kHz filter. The signals are all similar showing the mode is aliased in fig. 3. In pulse 25940 from the same series fast data show that the mode structure and amplitude is very similar to that in pulse 25937 of fig. 3, but the structure is shifted near the Nyquist frequency (125kHz). The filter outputs for this case are also given in fig. 4, showing the sensitivity of the filters.

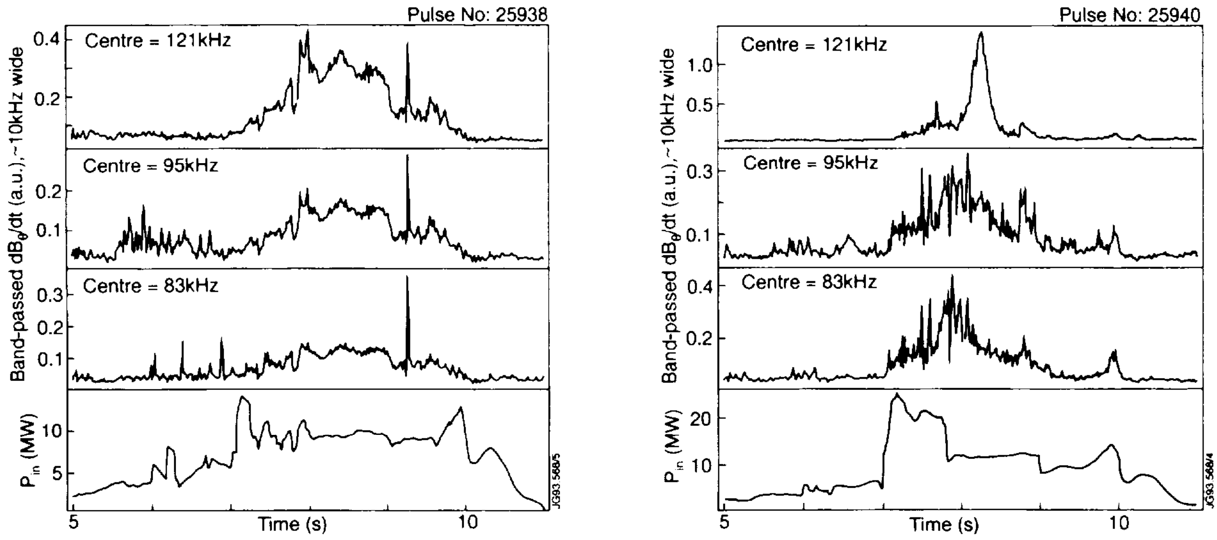

Fig. 4: Band-pass filtered magnetic data, with filters centred on 83, 95 and 121kHz for pulses 25938 and 25940. The mode is observed in the latter case on the 121kHz channel, but not in the former showing that the spectrum for this pulse in fig. 3 is aliased.

The frequency of the centre of the structures observed is plotted against the expected TAE frequency, for several pulses in fig. 5. This provides strong evidence for the identification of these modes as TAE.

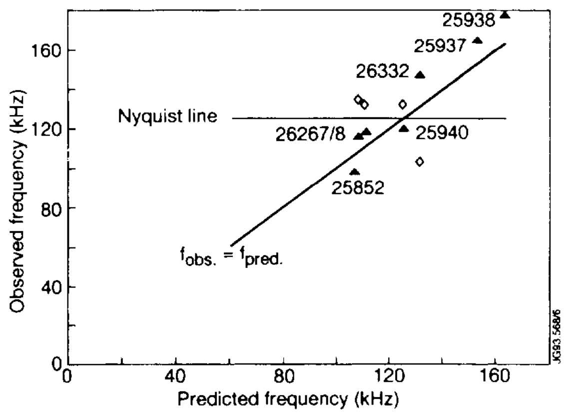

Fig. 5: Comparison of observed frequencies with the simplified TAE prediction $f_{TAE} \sim v_A / 4\pi qR$*, with* $q = 1.5$*. The open diamonds represent possible aliased values which could not be excluded.*

- Pulses 25940, 25937 and 25938 are all with a toroidal field of 2.8T and these show agreement with the expected density scaling.
- Pulse 26268 has the same density as 25937, and these show agreement with the expected toroidal field scaling.
- In the remaining pulses both the density and toroidal field are different to 25937.

The amplitude of the mode, obtained from the band-pass filters is plotted as a function of ICRH power in fig. 6. At the lowest power of 4MW in this scan magnetic power spectra reveal that a small mode (with amplitude ~1mG, below the band-pass filter noise levels) still exists. There is no marked changed in the structure of the frequency spectra at different ICRH input powers.

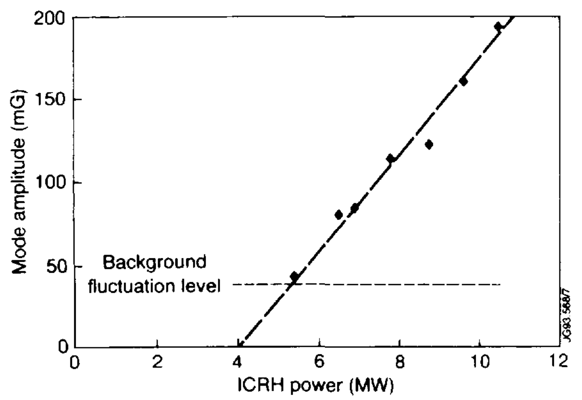

Fig. 6: Variation of peak mode amplitude with ICRH input power, suggesting a stability threshold near 4MW.

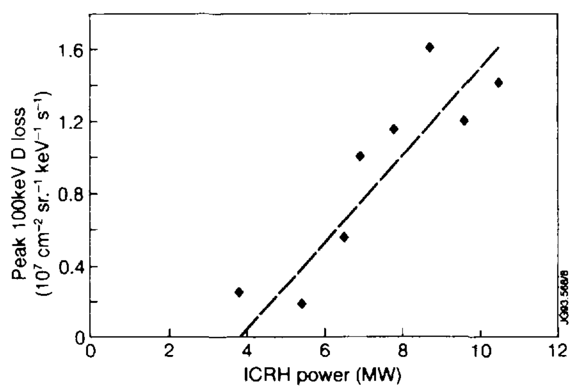

Fig. 7: ICRH power dependence of peak deuterium loss flux for the power scan of fig. 6.

- The dependence is close to linear with ICRH power in this range.
- A stability threshold near 4MW is suggested.

The neutral particle analyser gives information on particle losses at energies of up to 100keV in these pulses. When ICRH is applied, a small burst of particle loss is seen over a wide range of energies (50-100keV). It rises and peaks while the mode is present, subsequently decaying probably due to increasing shielding from the rising background density (an example of the time evolution is given in fig. 8). Fig. 7 shows the scaling of the peak loss with ICRH power for the same power scan as in fig. 6.

- The two phenomena appear to be temporally linked, and show the same power threshold.
- Further analysis is needed to determine whether a casual relationship exists between the two.

The typical time evolution of the TAE mode is shown in fig. 8. Fast data at 16.5s show mode activity in the 100-125kHz range. The rms level of this activity is detected by the 121kHz and 95kHz band-pass filters. The rising H-mode density would shift the TAE frequency from ~110kHz to ~90kHz in the period 16.5-18s. A shift towards the lower frequency filter is evident, but at 17.5s the outputs of both filters have decayed, implying that the mode is stabilised. This behaviour may be due to increasing Landau damping with the increasing density, or possibly due to increasing β_p which is also predicted to stabilise TAE activity [10]. This pattern is observed in several pulses so that

- the TAE is (usually) transiently destabilised in JET for a duration of the order of 1s.

Fig. 8 also shows the interaction of the mode with sawteeth, which sometimes quench the mode when it is large and destabilise it when it is small, possibly due to a rearrangement of fast particles in the plasma.

Some high frequency modes in JET have previously been identified as possible ELM precursors [11]. The example in fig. 9 shows that these modes are distinct from the TAE activity. The spectrum given for pulse 25941 shows both modes simultaneously present, and only one shows correlation with the D_α light variations.

In the preceding pulse, 25940 (with lower impurity levels), the plasma is ELM-free and the lower frequency mode is absent, while the TAE is present and is virtually identical to that in pulse 25941 of fig. 9. Another example of the lack of a relation to ELMs is in pulse 25852 (of fig. 1), where the TAE appears during an ELMy phase and continues to grow after the end of the ELMy phase.

4. CONCLUSIONS

A new high frequency mode has been observed in JET. This shows features expected of the toroidicity-induced Alfvén eigenmode, including the new observation of bi-directional travelling waves, a characteristic of Alfvén waves. The only other coherent mode in the same frequency range identified in JET is that suggested as an ELM precursor. The data show a clear distinction between the two.

TAEs are observed with both neutral beam injection and ICRH heating. In the former case the beam speed is sufficient to excite only the $v_{parallel} = v_A / 3$ resonance, so that the theoretical prediction of this resonance is supported.

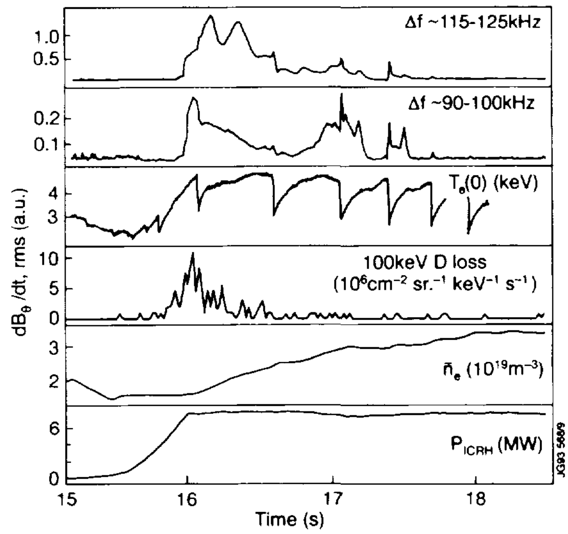

Fig. 8: Appearance of mode with application of ICRH. The mode subsequently decays as the high performance plasma develops. It is affected by sawteeth, and appears to be related to a burst of particle loss.

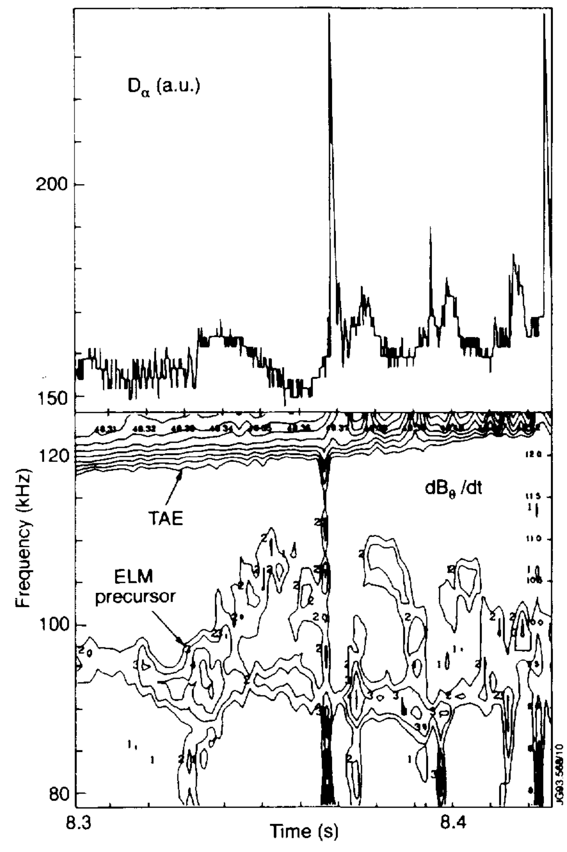

Fig.9: Example showing distinction between possible ELM precursors and TAE activity. The preceding pulse, 25940, is ELM free and only the higher frequency mode is seen in that case, with no apparent difference.

The data suggest a loss of high energy neutral particles correlated with the TAEs. Further study is needed to establish whether or not a causal relationship exists between the two.

In many cases the mode appears transiently, for a period of the order of 1s. This suggests that stabilising terms increase as the plasma equilibrium develops towards a higher performance discharge.

The conditions under which TAEs are observed in JET are not unusual. The modes may therefore be commonly present in JET, their observation being limited by availability of data.

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