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Alfvén Eigenmode Excitation by ICRH Beat-Waves

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ABSTRACT

The resonant excitation of Alfven Eigenmodes by ICRH beat waves has been attempted experimentally on JET tokamak plasmas. Toroidicity induced AE are excited when the difference frequency between two ICRH antennas is of the order of the central frequency of the relative Alfven continuum gap. The relatively large amplitudes for the TAE driven by ICRH beat waves suggest that this new non-linear excitation mechanism could allow investigations into the effects of AE on particle orbits and should be taken into account in ICRH heated thermonuclear plasmas.

Alfven Eigenmodes, AE [1], can be excited in tokamak plasmas in three ways. First, resonant wave-particle interaction can drive the modes unstable if the fast ion diamagnetic frequency, ω^*, exceeds the mode frequency and if the relevant driving rate overcomes the mode total damping rate. ω^* derives from the fast particle pressure gradient, which constitutes the free energy source for the AE excitation. In present devices, particles that resonate with the AE, with $v \sim v_{Alfven}$, can be produced by Neutral Beam Injection, NBI, and Ion Cyclotron Resonance Heating, ICRH and are seen to destabilise TAE modes [2-5]. In thermonuclear ignited plasmas, a significant fraction of the slowing down alpha population will be resonant with the AE. Large energy content and pressure gradients for these fusion produced alphas might lead to the excitation of large amplitude AE. The overall performance of a tokamak reactor could therefore be affected by the AE-induced modifications to the alphas' orbit characteristics [6]. These changes could lead to enhanced radial transport, particle losses and modifications to the plasma heating profiles, effects which have motivated both theoretical and experimental investigations into the physics of AE.

The second method of AE excitation is based upon the use of antennas, external to the plasma but located inside the vacuum vessel, fed with an oscillating current providing a linear magnetic perturbation at the plasma edge in the AE frequency range. Such linear excitation, associated with sweeps of the driving frequency across the range of interest and with coherent detection of the plasma response, has the unique advantage of providing direct measurements of the AE damping rates, together with frequency spectra and mode structures [7]. The AE linear stability can therefore be studied in different tokamak plasma scenarios. These active experiments based on the use of the JET saddle coils have shown the existence of AE with high quality factors, $Q = \omega/\gamma$ up to 10^3-10^4, both in ohmic and additionally heated plasmas [7,8].The coupling to the plasma centre depends upon the profiles of plasma density and safety factor, q. For the existing arrangement at JET, the amplitude of the antenna driven AE never exceeds $\delta B/B \sim 10^{-6}$ at the edge, never approaching an amplitude at which significant perturbations to the particle orbits can be produced. In addition, the geometry of the JET saddle coil antennas allows mode selection only for relatively low toroidal mode numbers ($|n|<4$).

In this Letter we focus our attention on a third method of AE excitation, based on non-linear mechanisms, and specifically on the use of ICRH waves beating at the AE frequency. The motivation for this investigation is threefold. Firstly, the large power available in the JET ICRH systems, $P_{ICRH}>10MW$, can in principle lead to the excitation of large amplitude AE, allowing studies of the problems of particle orbit modifications.

Secondly, the excited modes are not bound a priori by a geometrical antenna structure characterised by a low-n toroidal spectrum. As the resonant absorption region for ICRH can be localised both toroidally and radially, AE with high n numbers could in principle be driven. In addition, if the high frequency waves are subject to strong local absorption, the beat wave excitation takes place in the plasma core directly, avoiding the problem of MHD accessibility from the vacuum region affecting the linear driving method using an external antenna.

Thirdly, as ICRH systems generally use independently driven modules, the effects on the plasma of frequency differences in the AE range need to be assessed in detail. For tokamak ignition experiments, this assessment could lead either to imposing upper and lower limits on the difference frequency of the ICRH modules, in order to avoid excitation of weakly damped AE, or to adopting specific combinations suitable for driving particular beneficial modes. Local AE excitation even for relatively strong AE damping, when the AE have no global effects on the plasma behaviour, could also lead to anomalies in the ICRH absorption characteristics.

The ICRH operational scenarios can be classified according to the amount of wave absorption per pass. With strong absorption, typically with more than 20% of the wave energy absorbed per pass, the ICRH resonant areas of the high frequency waves should overlap and coincide with the AE localisation region for a strong AE driving term to exist. Conversely, with only low RF wave absorption per pass, <<20 %, the vessel acts as a resonant cavity, with the wave energy being evenly distributed in space. The problem of overlapping with the AE resonant layer disappears, but the lower intensity of the uniformly distributed wave electric fields may lead to lower AE amplitudes.

Several mechanisms giving rise to non-linear coupling generating a beat wave at the ICRH difference frequency can be postulated. The non-linearity can be due to a coupling between current oscillations in ideal MHD, both in the case of local resonance overlap and of global ICRH field beating. In non-ideal MHD, the non-linear coupling can also take place between density oscillations associated with ion Bernstein waves. In this case it is expected that modes with finite density perturbations, such as the kinetic modes observed during experiments on antenna driven AE [8], be preferentially driven. Ponderomotive effects on particle orbits can also be at the basis of the low frequency beat wave generation. Finally, at the plasma edge, surface effects and antenna sheath rectification effects could play an important role in generating a source term at the ICRH wave difference frequency.

All these processes can either lead to a classical three wave process, involving the two ICRH waves and the AE itself, or, less directly, to the creation of an oscillating source at the difference frequency which in turn excites the global AE, acting as a virtual antenna. In the former case energy and momentum conservation laws give

$$f_1 - f_2 = \Delta f = f_{TAE}{}^0$$

$$\underline{k}_{\|1} - \underline{k}_{\|2} = \Delta\underline{k} = \underline{k}_{\|TAE} \sim 1/2qR \sim 0.1\ m^{-1}$$

where the last condition refers to a typical low n case. f_1, f_2 indicate the two ICRH wave frequencies, whilst $f_{TAE}{}^0$ refers to the frequency corresponding to centre of the toroidicity induced gap, within which the TAE exist. In the latter case only the frequency relation holds. Typically, for JET conditions, $f_{1,2} \sim 30 - 50$ MHz and $f_{TAE}{}^0 \sim 150$ kHz, so that $\Delta f/f \sim 0.3 - 0.5$ %. The volume averaged density and a q value of 1.5 are taken to calculate $f_{TAE}{}^0$, for simplicity.

The maximum theoretical efficiency of the conversion of the high frequency wave energy into the beat wave energy is given by the frequency ratio: $\eta_{max} = \max(P_{TAE} / P_{ICRH}) = f_{TAE}{}^0 / f_{1,2} <$ 1%. Particle orbits are expected to be modified substantially, becoming stochastic, when the AE perturbed magnetic field in the plasma core exceeds $\delta B/B \sim 5\ 10^{-4} - 10^{-3}$ [6], corresponding for the JET case to a volume averaged TAE power of the order of one kW, in the case of low poloidal mode numbers [9]. Considering a coupled power for two modules of 5 MW, this implies that significant perturbations in the particle dynamics should occur when $\eta > \sim 0.02\%$.

The JET ICRH system is composed of 4 independent modules driving antennas composed of four conductors, or straps, individually driven by four 2 MW tetrode amplifiers [10]. High absorption is usually obtained when the antennas are run in a dipole configuration, that is when the straps are phased 180^0 apart, whereas low absorption is typical of monopole and of fast wave current drive scenarios [11]. A complex control system has been implemented for phase, amplitude and matching control, which is based on the conversion of the RF frequency to an intermediate frequency (IF) in the range 1.1 - 1.5 MHz. Automatic matching via a minimisation of the reflection coefficient is guaranteed by closed loop frequency control or by mechanical adjustment of the line tuning elements (trombones and stubs) in open loop. In normal conditions the difference frequency between two different modules is less than 200 kHz and varies with the plasma coupling.

Two modes of operation are possible for the AE beat wave experiment. In the first, or passive mode, the ICRH plant operation is not affected. The IF frequencies of two different modules which are set with a common RF reference are mixed together to produce a reference/beat frequency, Δf, which drives the AE synchronous detectors (Fig.1). These will provide a measurement of any coherent activity at Δf from magnetic diagnostics and ECE, reflectometry, as in the active saddle coil experiments [7]. The output from the synchronous detectors is therefore a set of complex responses with a shared phase base. This base is that of the ICRH difference frequency rather than that of local oscillator as in [7].

In the second mode of operation, the active mode, two modules are chosen with the same RF reference frequency as above. One of them, the 'master', is operated in the normal configuration, with the automatic matching loop driving its actual frequency to maximise the coupling to the plasma. The IF of the first module is measured and summed in real time with f_{TAE}^0, calculated from pre-programmed values of the magnetic field and from on line measurements of the plasma density. A linear scan is added to look for resonances in the AE frequency range, with frequency sweep rates of 10 - 100 kHz/s. The total frequency is then imposed via the IF loop to the second module, the 'slave', so that $\Delta f = f_{TAE}^0$ + linear sweep (Fig. 2). The automatic matching control for the slave antenna is disabled; the available power is thus reduced. The mechanical tuning elements are frozen at an appropriate position in order to have a relatively good coupling to the plasma avoiding tripping the module. The ICRH antenna difference frequency acts as the reference for the TAE detectors as in the passive mode.

In the passive mode the difference frequency cannot be controlled and scans in the parameters determining the TAE dispersion relation, density or magnetic field, are necessary to identify the excitation of a TAE resonance. In Fig. 3 we show the first results of such experiments, with the ICRH antenna in a dipole configuration ($0\pi0\pi$ phasing for the four antenna straps) and in a hydrogen minority heating scheme, with $f_{1,2} \sim 43$ MHz. Two antennas are used, 180^0 apart toroidally, with powers coupled to the plasma $P_1 \sim P_2 \sim 1$ MW, so that no significant population of ICRF-heated ions can be produced to drive TAE via wave-particle interaction. The difference frequency of the two modules was kept approximately constant and the toroidal magnetic field was varied linearly in time. When Δf coincided with the TAE gap central frequency, a large response in the synchronously detected magnetic coil signal appeared. In Fig. 4 the same magnetic signal is represented as a function of the ratio of the beat frequency to the TAE frequency. The regular occurrence of a peak of activity when the frequency ratio was close to unity strongly indicates that this activity is linked to the TAE spectrum. Activity of smaller amplitude can also be seen at other frequency ratios (see Fig.4). The origin of these additional structures could be linked to other modes, since the beat-wave does not select any particular mode structure. The presence of several peaks with similar toroidal mode structures seems to indicate the occurrence of multiple kinetic AE [8]. However, the complex plane structures of the different diagnostic signals show that the observations of fine AE spectral characteristics can be strongly affected by the relatively broad band source and the associated frequency and phase reference for the coherent detection. The feedback system for automatic matching is characterised by a fast (5 ms) response, which translates in the low frequency wave-wave products into a significant frequency-noise level. Quantitative conclusions on the mode intrinsic frequency width, i.e. on its damping, are therefore not possible yet. The resonant character of the beat wave excitation is confirmed by the observed change in the spatial structure of the signal detected at a given Δf between the background, simply peaked at the antenna locations, and the resonant peaks of the response, characterised by a coherent structure on the toroidal plane.

This resonant excitation of modes for ICRH difference frequencies in the TAE range has been observed for a number of discharges (Fig. 5). During these experiments either the plasma density or Δf, via the automatic matching, was varied. When Δf crossed $f_{TAE}{}^{0}$, a strong response in the diagnostic signals was recorded. In Fig. 5 we show the observed peak amplitudes at the plasma edge on the magnetic pick-up coils in a number of discharges, represented as a function of the geometrical mean of the power coupled by the two antennas beating at Δf. It is important to note that the amplitudes of the beat wave driven AE are up to an order of magnitude larger than those typical of the saddle coil driven modes. Even though the observed amplitudes appear to be lower than those predicted to be necessary for producing stochastic particle orbits, preliminary investigations using neutral particle analysers indicate that in the largest amplitude case some modifications to the ion orbits may be occurring [12].

Typical results obtained during preliminary experiments in the frequency sweep mode of operation are shown in Fig. 6. Sweeps of about 30 kHz with rates of 10 kHz /s are imposed via the IF frequency to the difference frequency between two opposite antenna systems. An ICRH dipole configuration in a hydrogen minority heating scheme is used as before. The two modules are in this case located 45^0 apart toroidally and deliver powers $P_1 \sim 0.7$ MW and $P_2 \sim 0.45$ MW. The amplitude of the magnetic probe response at Δf is of the same order as in the case of resonant AE excitation in the passive mode. The modulation of the coupling via the modulation of the plasma position due to the 4 Hz JET divertor sweep and via the imposed scan to the slave antenna, however, prevents in this case a clear identification of the driven AE resonance.

In both modes of operation, different ICRH and plasma scenarios and possibly higher coupled ICRH power levels need to be investigated to obtain larger amplitudes for the non-linearly driven AE. ICRH schemes characterised by a lower absorption per pass or a better resonance overlap also need to be explored. Hotter plasmas, heated for example by non-resonant neutral beam injection, could also lead to improved non-linear coupling efficiency, particularly in conjunction with the excitation of kinetic AE.

To summarise, the resonant excitation of TAE by ICRH beat waves has been demonstrated experimentally for the first time. Damping and fine structure measurements appear to be currently prevented by the finite frequency width of the low frequency product of the non-linear wave-wave interaction. Nevertheless, the beat wave driven TAE are characterised by larger amplitudes than the modes driven linearly by external saddle coil antennas. Further experimental investigations and theoretical work are necessary to assess which non-linear mechanism is dominant and to identify ICRH and plasma scenarios characterised by a higher non-linear coupling efficiency. These preliminary results in a high absorption per pass ICRH scenario suggest that relatively large amplitude AE can be driven by the beating of two ICRH waves and that such a phenomenon needs to be taken into account when considering the use of ICRH in thermonuclear plasmas. In fact we should be careful when interpreting the excitation of TAE modes when using multiple ICRF launchers, especially when individually tuned to optimise their separate matching.

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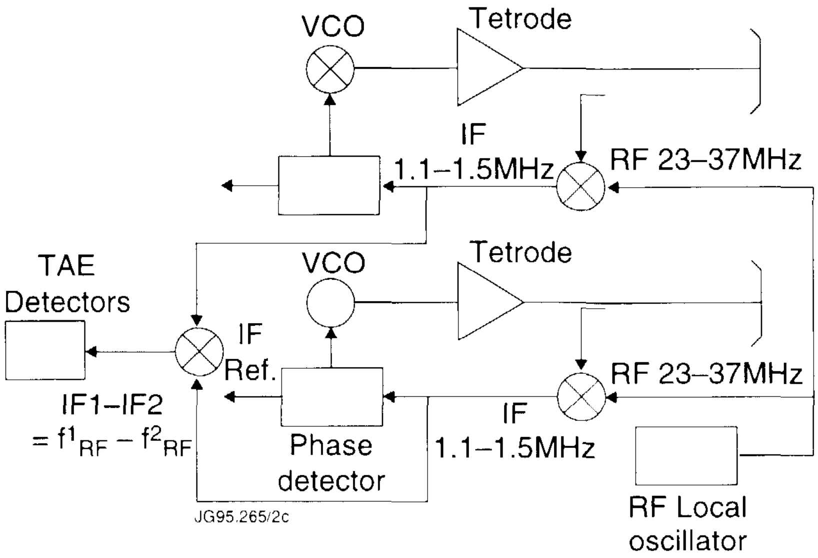

Fig.1: Experimental set-up for the excitation and detection of AE by ICRH beat wave: passive mode.

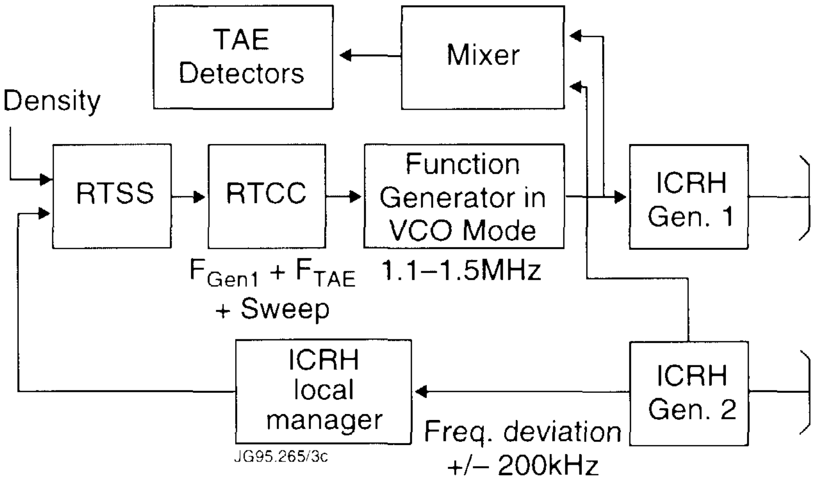

Fig.2: Experimental set-up for the excitation and detection of AE by ICRH beat wave: active, or frequency sweep mode.

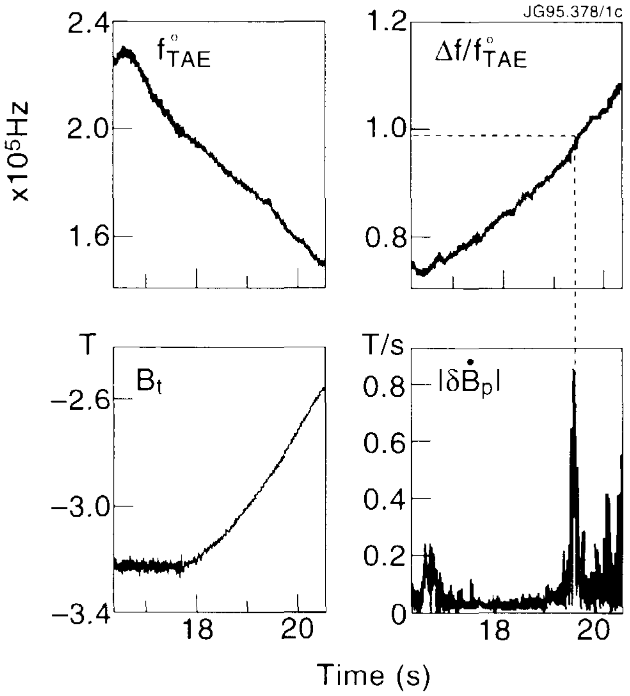

Fig.3: Passive mode: observation of an AE resonance on a magnetic probe located above the tokamak outer mid-plane when $\Delta f \sim f_{TAE}^0$. The power coupled to the plasma by each module is about 1MW, with a coupling resistance, $R_c \sim 2$ Ohm. Two antenna in a dipole configuration and 180° apart toroidally are used. JET shot #35051. Plasma current, electron temperature and average plasma density are, respectively, $I_p \sim 3MA$; $T_e \sim 5keV$; $T_{i0} \sim 3.5keV$; $<n> \sim 2\ 10^{19} - 1\ 10^{19} m^{-3}$; $\Delta f \sim 158-168kHz$.

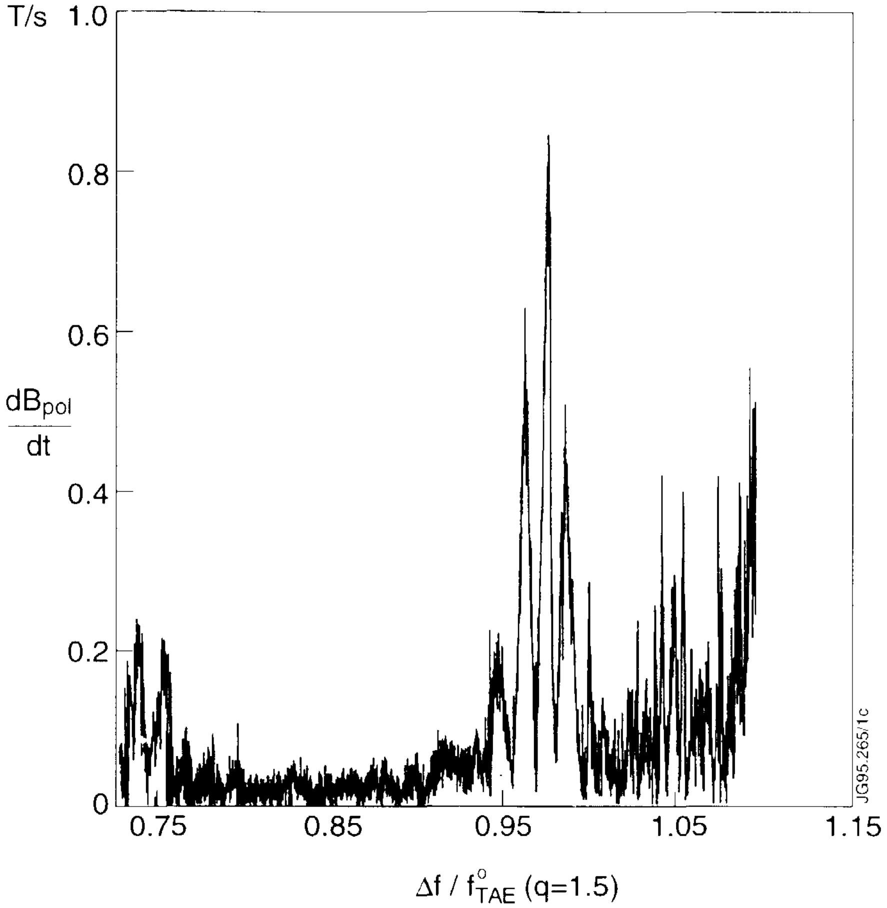

Fig.4: Detail of a magnetic probe response as a function of the ratio of the beat wave frequency to f_{TAE}^0 (for $q=1.5$) for the discharge shown in Fig.3.

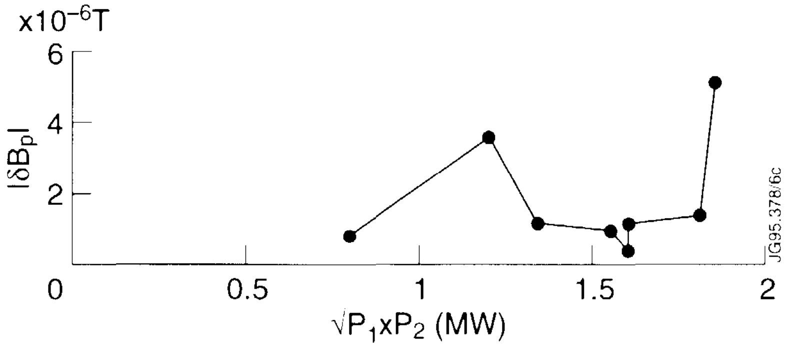

Fig.5: Amplitudes of the modes at $f\sim f_{TAE}^0$ driven at the difference frequency of two ICRH antennas and detected by magnetic probes located above the tokamak outer mid-plane, as a function of the geometrical mean of the two coupled powers. The same antenna configuration, with dipole configuration (0π0π) and about 180° apart toroidally, is used for all points.

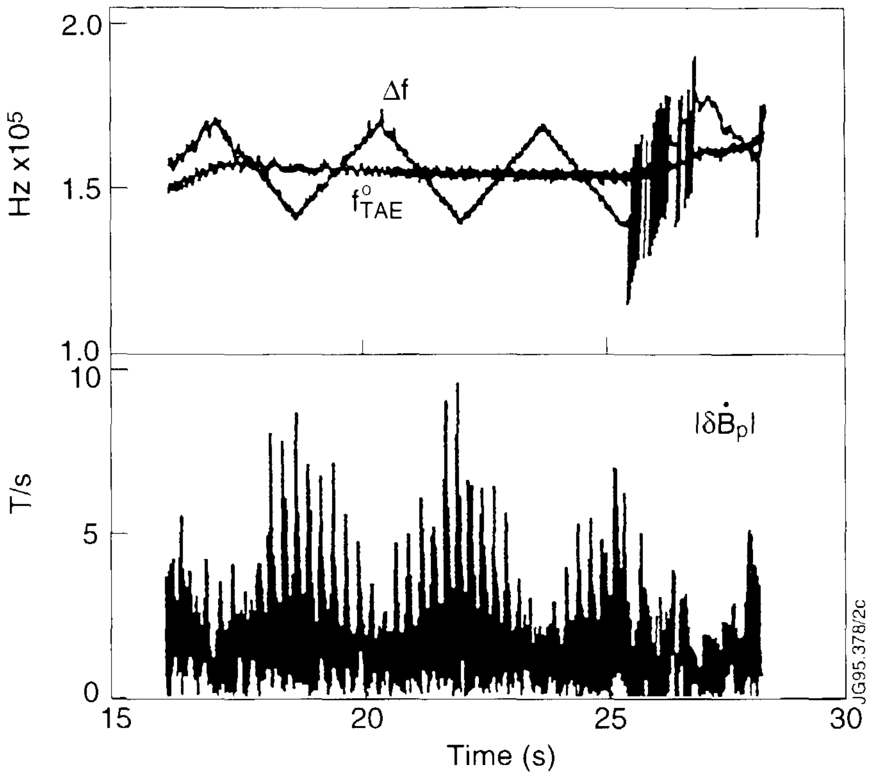

Fig.6: Active mode: f_{TAE}^0 and driven Δf, together with a synchronously detected signal of a magnetic probe located above the outer mid-plane. JET shot #35253; B_{tor}~2.6T; I_p~2MA; $<n>$~2 $10^{19}m^{-3}$; T_e~2keV. Two antennas coupling 0.7MW and 0.45MW to the plasma and 45° apart toroidally are used.