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ABSTRACT

The newly installed JET Alfven Eigenmodes (AE) active diagnostic is described along with the first experimental results. The aim of this diagnostic, which is based on external antenna excitation and synchronous detection of the plasma response, is a systematic study of the AE properties, in particular in terms of damping and stability. Direct information on frequencies, mode structures and, most importantly, damping rates of the excited global resonances can be obtained. TAE modes have been excited and identified by the dependence of their frequency upon magnetic field and density. The first direct measurements of the AE damping rates in different regimes corresponding to distinct dominant absorption mechanisms are reported.

1. INTRODUCTION

The understanding of the interaction between magnetically confined toroidal plasmas and fusion generated alpha particles is one of the key issues in the preparation of thermonuclear ignition experiments. In tokamaks and stellarators, energetic particles generated by fusion reactions or additional heating can excite via resonant interaction global Alfven Eigenmodes (AE), which can in turn trigger anomalous fast particle losses [1]. The parameter space over which ignition and safe operation can be achieved may be limited in the presence of these instabilities both by the induced degradation of alpha confinement and by the possible first wall damage due to localised energy deposition by the mode scattered resonant particles [2]. The natural occurrence of Alfven Eigenmodes is related to the balance between different damping mechanisms and the fast particle driving. AE spectra, mode structures and instability thresholds can be investigated by simply observing fluctuations in the appropriate frequency range [1]. Energetic particles driven AE activity has been reported for NBI and ICRH heated discharges in different tokamaks, including JET [3]. These passive measurements, however, cannot provide quatitative information concerning damping and driving effects. A more comprehensive understanding of the MHD activity in the Alfven regime can be reached via a study of the plasma response to externally driven perturbations. External antenna excitation and coherent detection of different probing signals at the edge and in the plasma core are combined in the Alfven Eigenmodes active diagnostic at JET. Such a diagnostic has the unique advantage of providing a direct measurement of the damping rates of the Alfven Eigenmodes in different plasma conditions.

2. EXPERIMENTAL SET-UP

i) Active antenna excitation

The JET saddle coil antennas are used to excite the Alfven Eigenmodes. The launching apparatus, developed to cover the frequency range of pressure, toroidicity and ellipticity induced AE (30 to 500 kHz), encompasses a remotely controllable function generator, a 3 kW broad band power amplifier, an impedance matching network, a power distribution and an isolation unit. The power distribution unit connects the amplifier output to the active antennas, allowing different combinations of antenna phasing that can preferentially excite specific toroidal and/or poloidal mode numbers (n: all, odd, even, (2,6,...), (4, 8,...); m: odd, even). Input current and voltage are measured at the distribution unit, whilst the voltage measurements on both the active and passive saddle coils are taken at the isolation unit. Currents on the saddle coils are measured at the end of the 80 m transmission line. Maximum currents and voltages induced in the saddle coils by the AE exciter in the present configuration are of the order of 30 A and 500 V, respectively. Correspondingly, the magnetic perturbations in the plasma are predicted to be such that $\delta B/B<10^{-5}$. As a result, the excited AE amplitudes are not expected to enhance the transport of energetic particles.

ii) Diagnostic method

The excitation frequency is swept across the shear Alfven gap regions, where AE are expected. The plasma response is extracted from background signals via homodyne detectors, providing in phase and quadrature components of the signals, or, in a complex representation, their real and imaginary parts. Different probing channels are considered: The voltage and current of the excited saddle coils provide the antenna impedance. The induced voltage on the passive saddle coils and the fast magnetic coils measure the perturbation of the radial and poloidal B-fields, allowing a mode analysis both in the poloidal and toroidal conjugate planes. Other non-magnetic diagnostics, such as heterodyne ECE and reflectometry, will be coupled to the synchronous detectors to reconstruct the radial structure of the excited global mode.

3. DATA ANALYSIS AND REPRESENTATION

The antenna-plasma-detectors transfer function can be directly obtained by dividing the complex amplitude of the different probes response by that of the current driven in the active antenna. The individual AE manifest themselves as resonances in the transfer function, which can be expressed as

$$H(\omega)=\frac{a+ib\frac{\omega}{\omega_0}}{1-(\frac{\omega}{\omega_0})^2+i\frac{2\gamma}{\omega_0}\frac{\omega}{\omega_0}}$$

where ω is the angular frequency of the exciter signal, ω_0 the resonance (real) frequency and γ the damping rate. a and b are real numbers that, for small damping ($\omega_0>>\gamma$), are proportional to the in phase and quadrature components of the detected signals. To represent the plasma resonance in terms of complex conjugated poles (p, p*) and residues (r, r*), the complex transfer function H is decomposed in partial fractions. If several (N/2) resonances occur in the measurement range, this representation reads

$$H(\omega,x)=\sum_{n=1}^{N/2}\frac{1}{2}\left(\frac{r_n(x)}{i\omega-p_n}+\frac{r_n^*(x)}{i\omega-p_n^*}\right)=\frac{B(x)}{A}$$

where $p=i\omega_0+\gamma$ and x indicates explicitly the space dependence of a diagnostic signal. B and A denote polynomials in $i\omega$ with real coefficients and degree N-1 and N, respectively. For a given resonance only the numerators (the residues) depend upon the position, whilst the denominators, i.e. the poles, are common. Since the signals may contain direct coupling with the antenna, an additional quantity, dependent upon position, must be added

$$H(\omega,x)=\frac{B(x)}{A}+D(x)=\frac{B'(x)}{A}$$

B'(x) can have a higher degree than B(x) to account for the antenna-probe coupling transfer function. The data analysis, based on the fit of a set of space resolved measurements of complex transfer functions with rational functions in $i\omega$ with real coefficients [4], leads to a representation of the eigenmodes in terms of complex poles and of the corresponding space dependent residues. The latter correspond to a measurement of the wave amplitude as a function of space, i.e. of the single mode structure. The pole provides two pieces of information. Its imaginary component gives the actual frequency of the mode, ω_0. When no fast particle driving terms are present in the plasma, the real part of the pole, γ, corresponds directly to the damping rate. For modes which are stable but for which a finite fast particle induced growth rate exists ($\gamma_{drive} \# 0$, $\gamma_{damping} > \gamma_{drive}$), γ is the difference between the damping rate and the growth rate: $\gamma = \gamma_{damping} - \gamma_{drive}$. The cases of marginally stable ($\gamma_{drive} \sim \gamma_{damping}$) and unstable modes ($\gamma_{damping} < \gamma_{drive}$) are more complicate and would necessitate a data analysis in terms of non-linear models. Note that the synchronous detection chain can also be used in passive mode, with the reference frequency being swept across the expected AE frequency domain, but with no current driven in the saddle coils. In this case the frequency and amplitude of an unstable mode can be estimated, but, due to the lack of knowledge of the driving source spectrum, no information on its damping can be gathered.

4. FIRST EXPERIMENTAL RESULTS

i) Passive studies

Preliminary passive studies using two saddle coils and five magnetic probes indicated some broad band ($\Delta f > 30$ kHz) activity around the TAE frequency, f_{TAE}, when neutral beam heating at moderate power is applied to the JET diverted plasmas ($f_{TAE} \cong v_{Alfven}/(4\pi q R_0)$ and $v_{Alfven} = B/(4\pi n_i m_i)^{1/2}$) . These studies helped in identifying the frequency domain of interest for the first phase of the active studies, which have subsequently been undertaken in the range 60-180 kHz.

ii) Results with active AE excitation

In this region several Eigenmodes have been clearly observed in the ohmic phases of JET pulses in different plasma configurations. An example of a resonance seen in an ohmic plasma is shown in Fig.1. When the frequency is swept across the resonance, the magnetic probe signal amplitude describes a circle in the complex plane. The maximum value of the perturbed magnetic field measured by the pick-up coil is of the order of 10^{-6} T. The relatively low damping rate ($\gamma/\omega \cong 1\%$) seems to suggest the absence of continuum damping.

iii) Eigenmode identification

To verify the 'Alfvenic' character of the observed resonance, the dependence of the observed resonance frequency upon the magnetic field and density was investigated. In the first case (Fig.2) only the toroidal magnetic field is varied. The measured frequency agrees with f_{TAE} calculated with the simplifying assumption that q=1.5, which for realistic JET profiles corresponds to the most unstable TAE mode [5]. The damping coefficient is not observed to vary throughout the scan. Fig.3 shows a case in which the density is varied, with toroidal field and plasma current practically constant. The observed mode frequency follows the calculated f_{TAE}. These two results clearly show that the observed resonances are related to the Toroidal Alfven Eigenmodes. Quality factors ($Q=\omega/\gamma$) of the order of ten at the beginning of the scan suggest that in this regime continuum damping can be responsible for the mode absorption. After t≅49s, the profiles are modified in such a way that $n(r)q^2(r)$ becomes approximately constant, and a second regime, in which the Alfven gaps are open and no continuum damping is possible, is entered.

iv) Effect of variations in the plasma current

A scan in the plasma current, for constant toroidal field, was performed in shot #31638. Variations in the mode frequency as well as in its damping coefficient clearly appear in the AE data (Fig.4). The observed frequency does not follow the simply calculated f_{TAE}, for fixed values of q and for densities taken at the corresponding radial position, but it increases as the plasma current is raised. The mode structure does not vary significantly throughout the scan, as shown in the poloidal reconstruction reported in Fig.5 for two different times. An increase in the plasma current produces an outward displacement of the resonant surface corresponding to a fixed value of q (e.g. q=1.5). The corresponding variation of the density along the radial profile would translate into a variation of v_{Alfven}, and thus of f_{TAE}, which is compatible with the observed Eigenmode frequency variation. A quality factor larger than 100 seems to exclude the presence of continuum damping for this shot and is consistent, for its order of magnitude and its variation with the density, with the predicted effect of electron Landau damping [6].

v) Effect of additional heating

Preliminary results concerning AE excitation in the presence of fast particles generated by NBI and/or ICRH indicate that the damping rate is changed by additional heating. Experiments with the AE active diagnostic in conjunction with NBI, IRCH and Lower Hybrid additional heating, current drive and profile control, are under way.

5. CONCLUSIONS

The combination of external antenna excitation and synchronous detection of the plasma response constitutes the basis of the Alfven Eigenmode active diagnostic at JET. The experimental apparatus has been installed and tested and the diagnostic method has been successfully demonstrated. MHD global modes have been excited and identified as Alfven Eigenmodes by the dependence of their frequency upon the density and the toroidal magnetic field. The damping rates of TAE modes have been experimentally measured for the first time. Control of antenna phasing and space resolved magnetic measurements allow a determination of the excited mode structure. These experimental investigations on the behaviour and specifically on the damping, of the Alfven Eigenmodes in JET, complemented by MHD and kinetic modelling, are expected to provide an important contribution to the assessment of the Alfven Eigenmode stability in future thermonuclear experiments.

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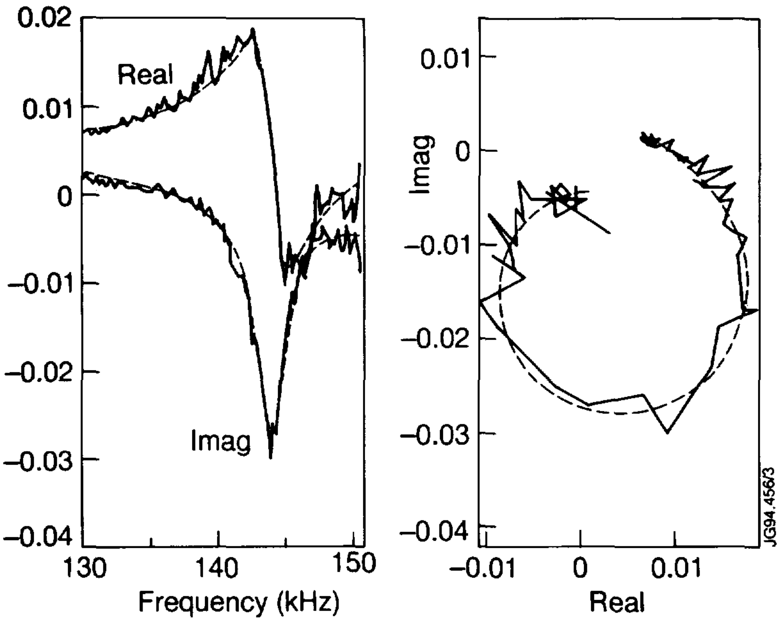

Fig.1 *Example of experimentally observed TAE resonance in the ohmic phase of JET shot #31638. Left: Real and imaginary part of a magnetic probe response. Right: Complex plane representation of the same signal. In both cases the signal is normalised to the exciter current. A fit with a rational fraction of order 5/2 is also shown. The fit gives f=144.2 kHz ($\delta f<100$ Hz), $\gamma=1400$ s^{-1}($\delta\gamma<100$ s^{-1}). $B \cong 2.8$ T, $I_p \cong 2.2$ MA, line integrated density $\cong 7x10^{19}$ m^{-3}. Two active saddle coils (on the top of the machine, in opposite octants, 1 and 5) with the same phase are used.*

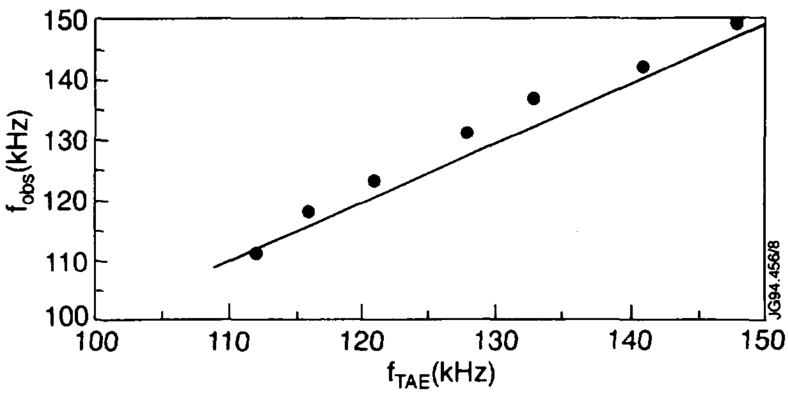

Fig.2 *Variation of the measured Eigenmode frequency with toroidal magnetic field (#31591). In the interval considered B is varied linearly between 2.2 T and 3 T. The density and plasma current are kept constant. The same saddle coils as in Fig.1 are active, but with opposite phase. Here and in Fig.3, f_{TAE} is calculated for constant q (q=1.5).*

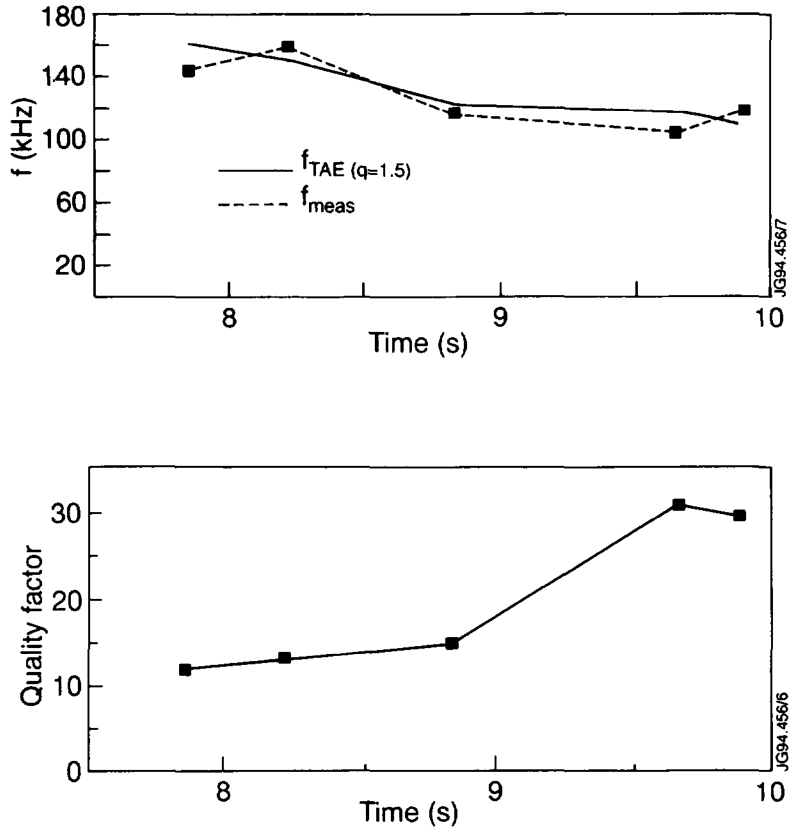

Fig.3 *TAE frequency (top) and quality factor (bottom) for different densities within JET shot #31150. The line integrated density varies between $5.2x10^{19}$ m^{-2} and $11x10^{19}$ m^{-2}; $B \cong 2.7$ T, $I_p \cong 2$ MA. One active saddle coil on the top is used.*

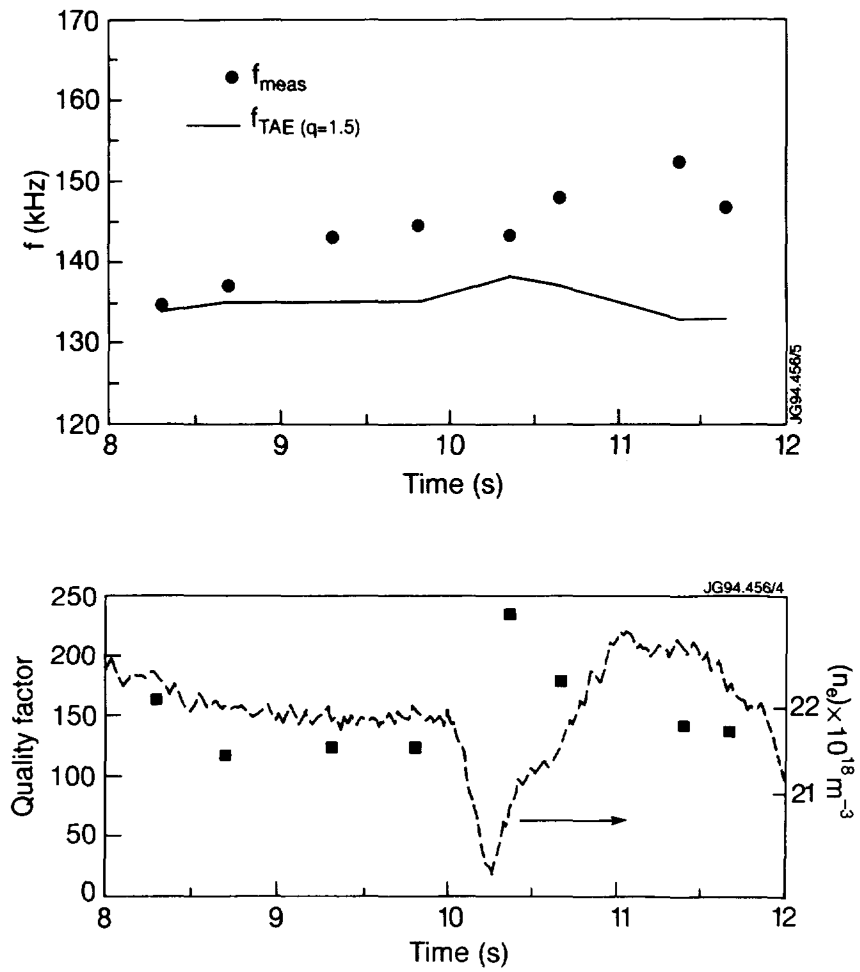

Fig.4 *Evolution of the observed frequency (top) and quality factor (bottom) of a global Alfven mode with increasing plasma current (JET shot #31638, as for Fig.1). The variation of density is also indicated (bottom).* I_p *is scanned linearly from 2.17 MA to 2.6 MA;* $B \cong 2.8$ *T.*

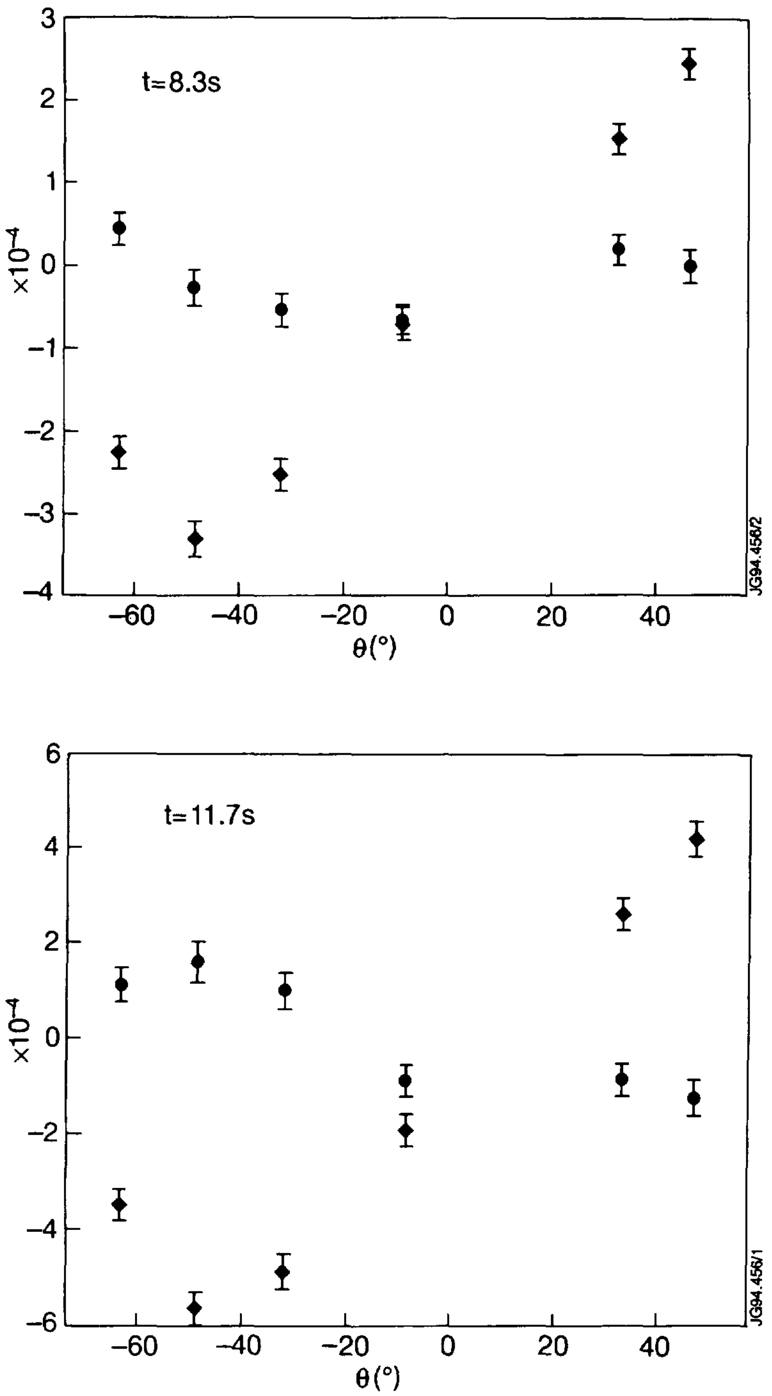

Fig.5 *Poloidal mode structure reconstruction for two different times of the current scan reported in Fig.4. Top: t=8.3 s; Bottom: t=11.7 s. Real (•) and imaginary (♦) components of the Eigenmode residues are plotted vs. the poloidal angle. As in Fig.1 the magnetic signals are normalised to the active saddle coil current.*