Observation of Multiple Kinetic Alfvén Eigenmodes

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Multiple weakly damped Alfvén eigenmodes (AE) have been excited and detected by means of a dedicated active diagnostic in JET tokamak plasmas heated by ion cyclotron resonance heating, neutral beam injection heating, lower hybrid heating, and high plasma current Ohmic heating. This phenomenon is interpreted in terms of a new class of AE, the kinetic AE, predicted in theoretical models which include finite Larmor radius and toroidicity effects.

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A number of electromagnetic collective processes may affect, through wave-particle interaction mechanisms, the dynamics of the alpha particle population generated by deuterium-tritium fusion reactions in magnetically confined thermonuclear plasmas. Amongst these, weakly damped Alfvén eigenmodes (AE), global discrete modes existing within the shear Alfvén spectrum in toroidal devices [1], can interact resonantly with the fusion produced alpha particles during their slowing down, being driven unstable and in turn affecting their orbits [2]. Above a certain threshold amplitude, AE can cause stochasticity of particle trajectories and consequently anomalous phase space particle transport and losses. Together with the mode phase velocities and spatial distributions, the number of modes simultaneously present determines the stochastic threshold and thus the related transport phenomena. Typically, the larger the number of modes, the lower the threshold [3].

Over the last few years much attention has been given to toroidal AE (TAE) within the framework of ideal magnetohydrodynamics (MHD) [4]. The recent inclusion of kinetic effects into the description of TAE in warm plasmas has produced two new results: a novel absorption mechanism for TAE, referred to as radiative damping, and the appearance, in the frequency range associated with the TAE, of new families of weakly damped discrete modes, the kinetic TAE (KTAE) [5]. As KTAE are intrinsically exempt from radiative damping, with continuum damping replaced by mode coupling between KTAE with frequencies above the TAE gaps [5], their total damping rates and instability thresholds can be lower than those of the TAE. Several KTAE may be associated with every TAE gap. The number of KTAE that can be simultaneously excited can thus be much larger than the number of TAE, and the relative stochastic threshold amplitude could be reduced significantly.

On the JET tokamak, direct antenna excitation combined with coherent detection of the driven plasma response allows investigations into the spectral features and the damping of linearly stable AE with low toroidal mode numbers, $|n| < 4$, independently of fast particles driving [6]. For Ohmically heated, relatively cold plasmas, the driven and detected AE spectra were characterized by a very small number of modes in the TAE gap, with damping rates covering a wide range for only slightly differing plasma configurations, $0.1\% < \gamma/\omega < 10\%$ [6]. In this Letter we report the regular experimental observation of multiple peak structures in the TAE frequency range, characteristic of hot JET deuterium plasmas, whenever they are heated by any of ion cyclotron resonance heating (ICRH), neutral beam injection (NBI), lower hybrid heating (LHH), and high current Ohmic heating independently of the presence or not of fast particles.

Two of the four lower JET saddle coils were used as external antennas in an $|n| = 2$ configuration to excite modes in the frequency range 60–300 kHz [6]. Currents and voltages applied to the saddle coils did not exceed 15 A and 300 V, generating oscillating magnetic fields well below the levels predicted to produce significant perturbations to the particle orbits. Different types of diagnostic signals were synchronously detected to extract the plasma response associated with the driven waves. Pickup coils provided a measurement of the perturbed poloidal magnetic field at several locations at the plasma periphery, while signals from a multichannel microwave reflectometer gave information on the density perturbations at the saddle coil driving frequency at different radial locations inside the plasma. The diagnostic method requires repetitive sweeps of the driving frequency. The overall time and frequency resolution of the frequency and damping measurements are interdependent and linked to the frequency sweep rate. The latter is limited on the upper side by the plasma noise and the integration time needed to extract the driven signal in the synchronous detectors, and on the lower side by the characteristic time scale for variations of the mode resonant frequency. Typical figures for the time and frequency resolutions were 0.2–1 s and 0.5–1 kHz, with

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sweep rates of 50–200 kHz/s. High resolution AE measurements are therefore limited to relatively stationary plasma conditions.

To observe the changes in the AE spectral features *during* a slow heating process and in the absence of resonant fast particles, an Ohmically heated discharge with a very slow current ramp-up, ≈0.33 MA/s from $I_p \approx 2$ to ≈4.1 MA, has been performed. The amplitude of driven poloidal field oscillations reported in Fig. 1 shows that the single peak TAE resonance observed for low values of the plasma current is transformed, later in the same discharge, into a multiple peak structure at higher plasma current, corresponding to a hotter plasma. Each individual peak corresponds to a plasma resonance, narrower than the single TAE, characterized by a smaller value of the damping rate. The increased baseline for the signal shown at the bottom of Fig. 1 may be attributed to different antenna-plasma coupling conditions and to the partial overlap of adjacent resonances. As these modes are externally driven with a dominant $|n| = 2$ component and the plasma toroidal rotation is negligible in JET Ohmic plasmas, they cannot correspond to Doppler shifted peaks of different n [7]. The extremely low excitation levels used and the linear dependence of the mode amplitude on the antenna current also exclude nonlinear antenna effects as the origin of these multiple peaks.

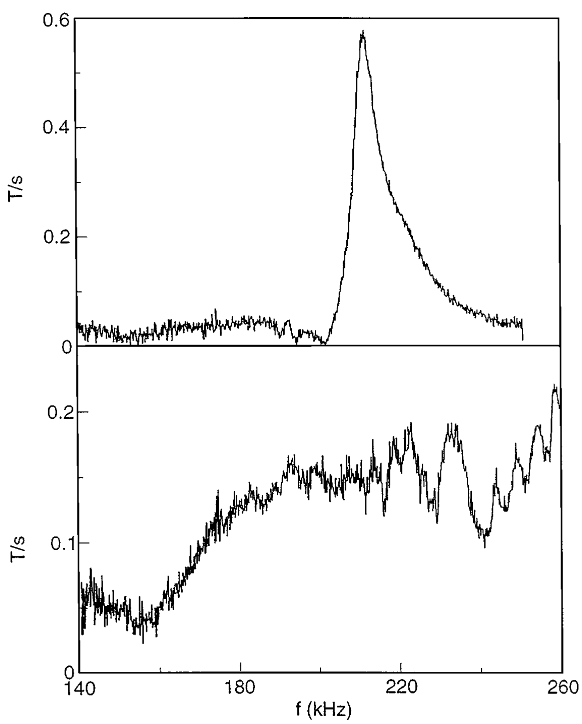

FIG. 1. B_{pol} probe signals for moderate (top) and high plasma current (bottom) in discharge 34073. The probe is located 33° above the tokamak outer midplane. Top: $t = 3.5$ s; $I_p \sim 2$ MA; $B_{\text{tor}} \sim 2.5$ T; $\langle n_e \rangle \sim 1.9 \times 10^{19}\ \text{m}^{-3}$; $T_e \sim 2.2$ keV. The single TAE has $f \approx 210.5$ kHz, $\gamma/\omega \approx 1.4\%$; the center of the TAE gap is $f^0_{\text{TAE}} = v_A/2\pi qR \sim 200$ kHz, calculated here and in the following considering $q = 1.5$ and the line averaged density. Bottom: $t = 9.5$ s; $I_p \sim 4.1$ MA; $B_{\text{tor}} \sim 2.9$ T; $\langle n_e \rangle \sim 3 \times 10^{19}\ \text{m}^{-3}$; $T_e \sim 3.2$ keV; $f^0_{\text{TAE}} \sim 180$ kHz.

An explanation of these new observations can be proposed in terms of modifications of the Alfvén spectrum due to finite Larmor radius effects and to a finite wave electric field parallel to the equilibrium magnetic field. Analytical models for hot plasmas predict that several weakly damped discrete modes with regularly spaced frequencies exist inside a potential well formed above the gap, analogous to a quantum harmonic oscillator [5]. The mode frequency spacing Δf is regulated by the nonideal parameter $\lambda = 4\, m\, s/(r_m \varepsilon^{3/2})\ \rho_i (3/4 + T_e/T_i)^{1/2}$ such that $\Delta f / f_{\text{TAE}} \sim \varepsilon\lambda$, where ρ_i is the ion Larmor radius, s is the local magnetic shear, $s = (r/q) dq/dr$, m the poloidal mode number, and $\varepsilon \approx 2.5 r_m/R$, with R being the tokamak major radius and f_{TAE} the frequency at the center of the associated TAE gap. λ needs to be calculated at the gap surface r_m, defined for the (m, n) mode as the location where the safety factor q is $q(r_m) = (m + 1/2)/n$. Although the lack of reliable measurements of the magnetic shear prevents a systematic comparison of different plasma equilibria, qualitative indications can be obtained from relative changes of λ for similar plasma configurations. When $\lambda > \gamma/\omega\ \varepsilon$, kinetic effects compete with the toroidicity effects in the gap region and produce the transition from a "cold" TAE predicted by ideal MHD models to multiple KTAE. Similarly, these kinetic effects are expected to affect the AE spectrum in the region of the ellipticity induced gap and to generate series of kinetic ellipticity induced AE, KEAE.

To investigate the modifications of the AE spectral characteristics produced by these kinetic effects, we returned to equilibria which previously yielded a simple TAE and increased the temperature and hence λ/γ by means of additional heating. The combination of LHH and moderate ICRH in an electron or minority heating scheme constitutes an ideal scenario as T_e, T_i, and T_e/T_i are raised, increasing λ while reducing AE kinetic damping without producing significant resonant particle populations. The latter might provide an additional driving source for AE, confusing the interpretation of the antenna-driven spectra. Figure 2 shows the spectrum of the driven magnetic and density perturbations under these conditions. Multiple resonances characterized by the same toroidal mode number, $|n| = 2$, appear simultaneously on both types of signals at frequencies above the center of the TAE gap estimated for $q = 1.5$, and these multiple AE have been clearly seen in the quasistationary heated plasma for 2.5 s. This first observation of driven density perturbations suggests an internal mode structure different from that of the cold TAE, for which no reflectometer signals were detected for similar excitation levels and magnetic probe response.

Comparable spectra in the TAE-EAE gap frequency range, with similar peak frequency spacing, resonance width and mode numbers, have been observed during discharges in which other additional heating methods were

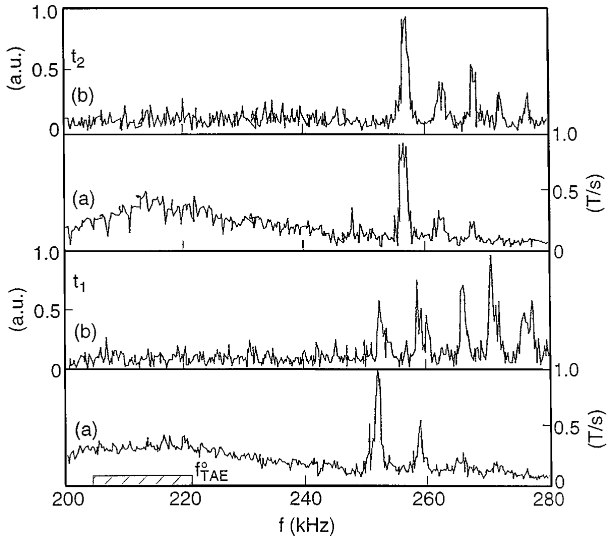

FIG. 2. Spectrum of magnetic (a) and density (b) perturbations in the TAE frequency range for a plasma heated by LHH (2.5 MW) and ICRH (6 MW), in an electron heating scheme (shot 33157). The probe is located 44° above the tokamak outer midplane. The reflectometer frequency corresponds to $r/a \sim 0.5$. Two successive scans, at $t_1 = 19$ s and $t_2 = 20$ s, are shown. $I_p \sim 3$ MA; $B_{\rm tor} \sim 3.2$ T; $\langle n_e \rangle \sim 2.5 \times 10^{19}$ m^{-3}; $T_e \sim 6.3$ keV; $T_i \sim 2.9$ keV. $\Delta f/f \sim 2.5\%$ and $\gamma/\omega < 10^{-3}$; $f^0_{\rm TAE}$ is indicated by the shaded region on the graph.

applied. Multiple peaks were observed with only LHH, on both magnetic and density fluctuation measurements. The absence of resonant fast particles and of plasma rotation, together with the observed central LHH power deposition profiles, guarantee clear, Doppler-free AE signals without significant distortion of the AE gap structure. In this case

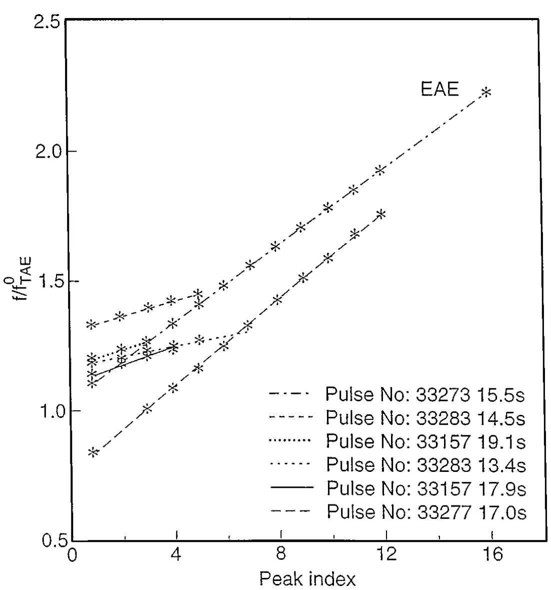

FIG. 3. Example of frequency distribution of the multiple AE driven by an external antenna for a number of additionally heated JET discharges. The peak index enumerates the AE from the lowest frequency peak observed in the TAE range.

λ/γ is enhanced mainly through an increase in the electron to ion temperature ratio ($T_e/T_i \sim 2$–3). A series of AE resonances around the TAE gap was also seen on the magnetic signals during NBI heating, despite some interpretative difficulties raised by sheared plasma rotation and the presence of resonant particles with a high beam energy, ~140 keV. ICRH heated plasmas in a hydrogen minority scenario for electron heating again showed multiple AE in the region of the TAE gap. As in the LHH case, relatively high magnetic field ($B \geq 2.8$ T) and intermediate power levels ($P < 6$ MW) allowed us to exclude significant effects of highly energetic trapped particles. Finally, very weakly damped ($\gamma/\omega < 10^{-4}$) multiple modes were seen, mainly on the reflectometer signals, during current ramp-down experiments, corresponding to sudden variations in the internal plasma inductance and presumably to rapid changes in the magnetic shear.

In all these cases the observed multiple peak structures associated with the driven AE were characterized by the simultaneous presence of several, at least 5, resonances with regular frequency spacing. An example of the peak frequency distribution for eigenmodes driven with a $|n| = 2$ antenna configuration during these additionally heated JET discharges is shown in Fig. 3. The peak

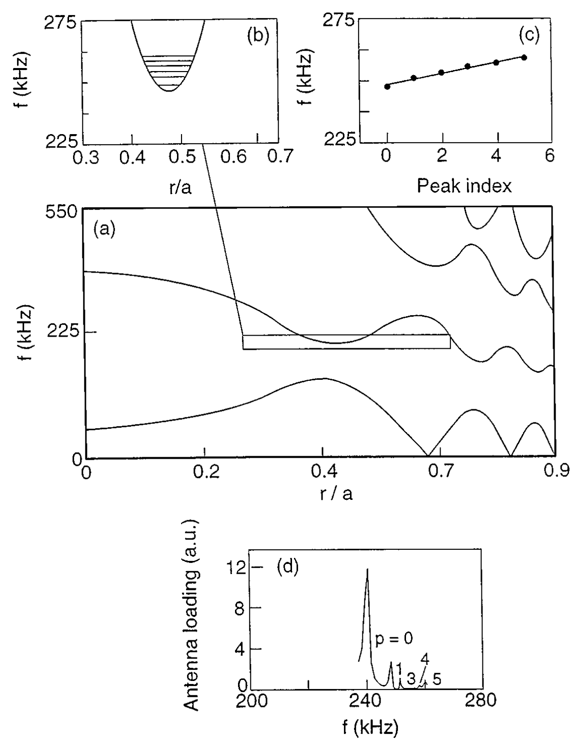

FIG. 4. Alfvén spectrum calculated by the CASTOR code for shot 33157 at $t = 19$ s. (a) Continuous spectrum $\omega(r) = k_{\|m}(r)v_A(r)$. (b) Effect of the splitting of the Alfvén continuum into discrete weakly damped KTAE in a hot plasma: detail of the most central minimum ($m = 2, 3$) in the continuous spectrum above a TAE gap. The KTAE eigenfrequencies are shown in (c) within the parabolic continuum and as a function of the peak index as in Fig. 3, corresponding to the radial mode number. (d) Calculated antenna-driven spectra.

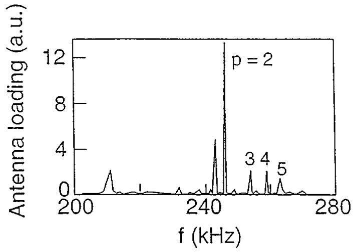

FIG. 5. Antenna-driven spectra computed by the PENN code for shot 33157 at $t = 19$ s.

spacing remained similar for consecutive sweeps when the plasma conditions were maintained approximately stationary (in comparison with the diagnostic sweeping time); the largest value of the frequency spacing is $\Delta f \approx$ 7.5–8.5 kHz and the largest number of the regularly spaced peaks is 12. A direct dependence of the observed frequency distribution upon the sweep rate was excluded experimentally. The damping rates were in most cases significantly lower than for the corresponding single cold TAE. Upper limits for γ/ω could be established experimentally and were in the range 10^{-3}–10^{-4}.

Two complementary numerical tools, the full wave code PENN [8] and the resistive MHD code CASTOR [9], were used to study the AE spectra and specifically to calculate the linear plasma response to external driving currents in the saddle coils for realistic plasma equilibria corresponding to multiple gaps. Hot plasma regimes could be investigated as both models include kinetic effects, via an expansion to second order in the ion Larmor radius in PENN [10] and via a complex resistivity term in CASTOR [11].

Figures 4 and 5 show the results of the two codes for the conditions of the experimental results reported in Fig. 2. In this case λ is estimated from the reconstructed plasma equilibrium to give $\varepsilon\lambda \approx 0.03$–$0.04$, in agreement with the measured values of $\Delta f = 6.25 \pm 1.25$ kHz at $f^0_{\rm TAE} = 213 \pm 7$ kHz. In Fig. 4 we see the continuum structure reconstructed by CASTOR (a), along with the eigenfrequencies of the KTAE associated with one of the TAE gaps (b), at $r/a \sim 0.5$. These are characterized by a regular spacing $\Delta f/f^0_{\rm TAE} = (1.3 \pm 0.3)\%$, uniquely determined by the nonideal parameter $\varepsilon\lambda$. For the constant $\lambda(r)$ assumed in the computation the KTAE spectral structure is in qualitative agreement with the experimental observations [Fig. 4(c), to be compared to Fig. 3, shot 33157, $t = 19.1$]. The calculated antenna loading as a function of frequency is shown in Fig. 4(d) (CASTOR) and Fig. 5 (PENN). Both curves indicate the presence of multiple peaks, corresponding to multiple plasma resonances, with frequencies and spacing similar to the experimental observations. Because of the plasma radial profiles, the frequency ranges of the TAE gap and the EAE gap can overlap. An identification of the origin of the different peaks therefore needs a reconstruction of the radial structure of the eigenfunctions. For the case of Figs. 2 and 4 the CASTOR results suggest that the externally driven modes, in the range 245–265 kHz, exist above the TAE gap at $r/a \sim 0.5$, corresponding to the eigenfrequencies shown in Figs. 4(b) and 4(c), whereas the PENN code indicates that most peaks are associated with modes localized within the EAE gap at the plasma edge, at $r/a \sim 0.9$.

In summary, multiple structures of weakly damped AE have been excited and detected in the TAE-EAE gap frequency range on the JET tokamak plasma via a new active diagnostic method, allowing MHD spectral studies with high frequency resolution. Contrary to the cold TAE case, in which no density oscillations were detected, these structures have been observed on the reflectometer diagnostic signals in the plasma core as well as on the magnetic probes. As they appear in experimental conditions which correspond to the predicted departure from ideal MHD behavior due to kinetic effects, including increased electron and ion temperatures, ion Larmor radius, electron to ion temperature ratio, and changes to the magnetic shear, the observed modes may belong to the general class of kinetic Alfvén Eigenmodes.

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