LRP 517/95 May 1995

Observation of Multiple Kinetic Alfvén Eigenmodes

A. Fasoli, J.B. Lister, S. Sharapov, D. Borba,
N. Deliyanakis, C. Gormezano, J. Jacquinot,
A. Jaun, H.A. Holties, G.T.A. Huysmans,
W. Kerner, J.-M. Moret, L. Villard

Observation of Multiple Kinetic Alfvén Eigenmodes

A.Fasoli[1], J.B.Lister[1], S.Sharapov, D.Borba, N.Deliyanakis, C.Gormezano, J.Jacquinot, A.Jaun[1], H.A.Holties[2], G.T.A.Huysmans, W.Kerner, J.-M.Moret[1], L.Villard[1]

JET Joint Undertaking, Abingdon, Oxon OX14 3EA, UK.

[1]*Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland.*

[2]*FOM Institute for Plasma Physics, Rijnhuizen, Nieuwegein, Netherlands.*

Abstract

A new class of weakly damped Alfvén eigenmodes, the Kinetic Alfvén Eigenmodes, predicted in theoretical models which include finite Larmor radius and finite parallel electric field effects, has been identified experimentally for the first time in JET tokamak plasmas. Multiple peak structures in the TAE frequency region have been excited and detected by means of a dedicated active diagnostic in deuterium plasmas heated by ion cyclotron resonance heating, neutral beam injection heating, lower hybrid heating and high plasma current ohmic heating.

Observation of Multiple Kinetic Alfvén Eigenmodes

A.Fasoli[1], J.B.Lister[1], S.Sharapov, D.Borba, N.Deliyanakis, C.Gormezano, J.Jacquinot, A.Jaun[1], H.A.Holties[2], G.T.A.Huysmans, W.Kerner, J.-M.Moret[1], L.Villard[1]

JET Joint Undertaking, Abingdon, Oxon OX14 3EA, UK.

[1]Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland.

[2]FOM Institute for Plasmaphysics, Rijnhuizen, Nieuwegein, the Nederlands.

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, 4].

Over the last few years much attention has been given to Toroidal Alfvén Eigenmodes (TAE) within the framework of ideal magneto-hydrodynamics (MHD) [5]. 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 Toroidal Alfvén Eigenmodes (KTAE) [6-9]. As KTAE are intrinsically exempt from radiative damping, with continuum damping replaced by mode coupling between KTAE with frequencies above the TAE gaps [7,8], their total damping rates and instability thresholds can be lower than those of the TAE. Several KTAE may be associated with every TAE gap. Thus, for a given plasma equilibrium, the number of KTAE that can be simultaneously excited can be much larger than the number of TAE and the relative stochastic threshold amplitude could be reduced significantly.

The external antenna excitation and identification of TAE with low toroidal mode numbers, $|n|<4$, in linearly stable conditions have been previously reported for a variety of ohmically heated, relatively cold plasmas [10]. The observed TAE frequencies and mode structures were in agreement with theoretical estimates. However, the measured damping rates for only slightly differing plasma configurations covered a wide range, $0.1\% < \gamma/\omega < 10\%$, due to the effect of different absorption mechanisms and specifically to continuum damping in the plasma core and at the edge, thereby emphasising the extreme sensitivity of the TAE damping rates to the details of the plasma equilibrium which limits comparisons with theoretical predictions.

In this Letter we report the experimental observation of multiple peak structures in the TAE frequency region in JET heated plasmas when the plasma conditions were altered to produce larger ion Larmor radii, higher electron and ion temperatures and larger electron to ion temperature ratios with respect to the previously reported cases, for which the Alfvén eigenmode spectra were characterised by a very small number of modes in the TAE gap. Different plasma heating methods were applied, including Ion Cyclotron Resonance Heating (ICRH), Neutral Beam Injection (NBI), Lower Hybrid Heating (LHH) and high current ohmic heating.

These experiments were performed on JET tokamak deuterium plasmas independently of intrinsic driving by fast particles, using a dedicated active diagnostic which combines direct antenna excitation with synchronous detection of the driven plasma response [10]. 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. Currents and voltages applied to the saddle coils during these experiments 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. Pick-up coils provided a measurement of the perturbed poloidal magnetic field at several locations at the plasma periphery, while signals from a microwave reflectometer gave information on the perturbed density 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 level and the integration time needed to extract the driven signal in the synchronous detection chain, and on the lower side by the characteristic time scale for variations of the plasma parameters which define the resonant frequency. Typical figures for the time and frequency resolutions in these experiments were 0.2 - 1 s and <1 kHz respectively, with sweep rates of 50 - 200 kHz/s.

The first evidence for transitions in AE spectral features when ion and electron temperatures were increased was obtained in high current ($I_p > 3$ MA), ohmically heated plasmas. 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, characterised by a smaller value of the damping rate. 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 [11]. The extremely low excitation levels used and the linear dependence of the mode amplitude on the antenna current also exclude non-linear antenna effects as the origin of these multiple peaks.

The most likely interpretation of these new observations in the light of current theories can be found in terms of modifications of the Alfvén spectrum due to finite Larmor radius effects and to a finite wave electric field parallel to the static 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 [6-9]. The occurrence of these kinetic effects is regulated by the non-ideal parameter $\lambda = 4\ m\ s\ /(r_m\ \varepsilon^{3/2})\ \rho_i\ (3/4 + T_e/T_i)^{1/2}$, 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. 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 Alfvén Eigenmodes, KEAE.

To confirm that the observed spectrum is linked to these kinetic effects, we returned to equilibria which previously yielded a simple TAE and increased the temperature and hence the lambda parameter 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 the value of lambda while reducing AE kinetic damping without producing significant resonant fast 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 characterised by the same toroidal mode number appear simultaneously on both types of signals at frequencies above the centre of the TAE gap estimated for q=1.5. This first observation of driven density perturbations, linked to a finite oscillating parallel electric field, emphasises the non-ideal MHD character of these modes.

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 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 the non-ideal parameter lambda is enhanced mainly through an increase in the electron to ion temperature ratio (T_e/T_i ~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, multiple peak structures were seen during current ramp-down experiments, corresponding to sudden variations in the internal plasma inductance and presumably to rapid changes in the magnetic shear. In this case the driven perturbations appeared mainly on the reflectometer signals from the plasma core and were characterised by extremely low damping rates for the individual peaks, $\gamma/\omega < 10^{-4}$.

The very low damping rates observed for the driven KTAE/KEAE suggest that wave-particle destabilisation by a significant population of resonant particles should be easier than for TAE/EAE. Using the synchronous detection chain in a passive mode, with the reference frequency still being swept, but with no current driven in the saddle coils, it was possible to detect eigenmodes driven unstable by resonant fast particles. Multiple peaks with $f > f_{TAE}^0$ were indeed observed in these passive measurements, shown in Fig. 3 for ~7 MW of ICRH combined with ~4 MW of NBI.

In all the cases reported, the observed multiple peak structures associated with the driven AE were characterised by the simultaneous presence of several, at least 5, resonances with regular frequency spacing. An example of the peak frequency distribution for eigenmodes driven during some additionally heated JET discharges is shown in Fig. 4. The peak spacing remained similar for consecutive sweeps when the plasma conditions were maintained approximately stationary. 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}, with no systematic variation in the damping for different peaks documented to date. In many cases each peak appeared to consist of several finer components, preventing reliable absolute estimates of the mode damping rate.

Two complementary numerical tools, the full wave code PENN [12] and the resistive MHD code CASTOR [13], were used to study the AE spectra and specifically to calculate the linear plasma response to external driving currents in the saddle coils in axisymmetric toroidal geometry and 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 [14] and via the introduction of a complex resistivity term in CASTOR [15, 16].

Figures 5 and 6 show the results of the two codes for the conditions of the experimental results reported in Fig. 2 and for the corresponding JET equilibrium. On Fig. 5 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 ~ 0.5. These are characterised by a regular spacing (c), in agreement with the experimental observations. The calculated antenna loading as a function of frequency is shown on Fig. 5(d) (CASTOR) and Fig. 6 (PENN). Both curves indicate the presence of multiple peaks, corresponding to multiple plasma resonances, with frequencies and spacing similar to the experimental observations. Due to 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 5 the CASTOR results suggest that the externally driven modes, in the range 245 - 265 kHz, exist above the TAE gap at r/a ~ 0.5, corresponding to the eigenfrequencies shown in Fig. 5 (b) and (c), whereas the PENN code indicates that most peaks are associated with modes localised within the EAE gap at the plasma edge, at r/a ~ 0.9. In addition to these kinetic modes labelled on the graph with their radial mode numbers, CASTOR and PENN obtain peaks in the spectrum of the antenna loading at ~210 kHz and ~240 kHz, respectively. The former is attributed to the KTAE family associated with the neighbouring TAE gap, at r/a ~ 0.75, whilst the latter corresponds in PENN to a mode within the TAE gap at r/a ~ 0.8. The relative coupling to the modes corresponding to the TAE or EAE gaps is found in both models to depend strongly on the details of the plasma density and safety factor profiles.

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

The reported experimental results show that multiple, very weakly damped eigenmodes can exist in the TAE/EAE range of the Alfvén spectrum in a tokamak plasma. These modes are potentially very important for tokamak reactor operation as they could render alpha particle orbits stochastic, degrading particle transport and confinement and modifying plasma heating profiles.

The Authors would like to thank J.A.Dobbing, P.Lavanchy, D.J.Campbell, A.Santagiustina and the whole JET Team for experimental support, and K.Appert and J.Vaclavik for useful discussions. The work was partly supported by the Fonds national suisse pour la recherche scientifique.

References

[1] C.Z.Cheng, L.Chen, M.S.Chance, *Annals of Physics* **161**, 21 (1985).

[2] D.J.Sigmar, C.T.Hsu, R.White and CZ.Cheng, *Phys. Fluids B* **4**, 1506 (1992).

[3] G.M.Zaslavsky, et al., *Usp. Fiz. Nauk.* **156**, 193 (1988).

[4] A.Fasoli et al., *Phys. Rev. Lett.* **70**, 303 (1993).

[5] A.D.Turnbull et al., *Phys. Fluids B* **5**, 2546 (1993); L.Villard and G.Y.Fu, *Nucl. Fusion* **32**, 1695 (1992).

[6] R.R.Mett and S.M.Mahajan, *Phys. Fluids B* **4**, 2885 (1992).

[7] J.Candy and M.N.Rosenbluth, *Phys. of Plasmas* **1**, 356 (1994).

[8] H.L.Berk, R.R.Mett and D.M.Lindberg, *Phys. Fluids B* **5**, 3969 (1993).

[9] B.N.Breizman and S.E.Sharapov, submitted to *Plasma Phys. Contr. Fus.* (1995).

[10] A.Fasoli et al., submitted to *Phys. Rev. Lett.*.

[11] E.J.Strait, W.W.Heidbrink and A.D.Turnbull, *Plasma Phys. Contr. Fusion* **36**, 1211 (1994).

[12] A.Jaun, Ph.D Thesis, *CRPP/EPFL Laboratory Report* **LRP 513/95** (1995).

[13] G.T.A.Huysmans, J.P.Goedbloed and W.Kerner, *Phys. Fluids B* **5**, 1545 (1993).

[14] S.Brunner and J.Vaclavik, *Phys. Fluids B* **5**, 1695 (1993).

[15] J.W.Connor et al., *Proceeding of XXI EPS Conf. on Contr. Fus. Plasma Phys.,* **v. 18B Part III**, p.616 (1994).

[16] S.Sharapov et al., *Bull. Amer. Phys. Soc.* **39**, 1566 (1994) and *JET Report* **JET-P(94) 61**, p.105 (1994).

Figure Captions

Fig. 1 B_{pol} probe signals for moderate (top) and high plasma current (bottom) in the same discharge #34073. Top: t = 3.5 s; $I_p \sim 2$ MA; $B_{tor} \sim 2.5$ T; $\langle n_e \rangle \sim 1.9\ 10^{19}\ m^{-3}$; $T_e \sim 2.2$ keV. The single TAE has f ≈ 210.5 kHz, $\gamma/\omega \approx 1.4$ %; the centre of the TAE gap is $f_{TAE}^0 = v_A / 2\pi qR \sim 200$ kHz. Here and in the following f_{TAE}^0 is calculated considering q=1.5 and the line averaged density. Later, at t=9.5 s (bottom) a multiple peak structure appears, with $\Delta f/f \sim 2$ %; $I_p \sim 4.1$ MA; $B_{tor} \sim 2.9$ T; $\langle n_e \rangle \sim 3\ 10^{19}\ m^{-3}$; $T_e \sim 3.2$ keV; $f_{TAE}^0 \sim 180$ kHz.

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

Fig. 3 Passive measurements: multiple peaks with ICRH and low power NBI. Shot # 34188, t~15 s. ICRH: electron heating scheme, P~7MW; NBI: P(80 kV)= 1.4 MW, P(140 kV)=1.6 MW; $I_p \sim 2.8$ MA; $B_{tor} \sim 3.1$ T; $\langle n_e \rangle \sim 2.5\ 10^{19}\ m^{-3}$; $T_e \sim 7$ keV; $T_i \sim 5$ keV; $f_{TAE}^0 \sim 200$ kHz.

Fig. 4 Example of frequency distribution of the multiple kinetic AE driven by an external antenna for a number of additionally heated JET discharges.

Fig. 5 Alfvén spectrum calculated by the CASTOR code for the equilibrium reconstructed for shot #33157 at t= 19 s. (a): continuous spectrum. (b): detail of the most central minimum in the continuous spectrum above a TAE gap. The KTAE eigenfrequencies calculated using complex resistivity are indicated within the parabolic continuous spectrum profile and are shown in (c) as a function of the radial mode number. (d): calculated antenna-driven spectra.

Fig. 6 Antenna-driven spectra computed by the PENN code for shot #33157 at t = 19 s.

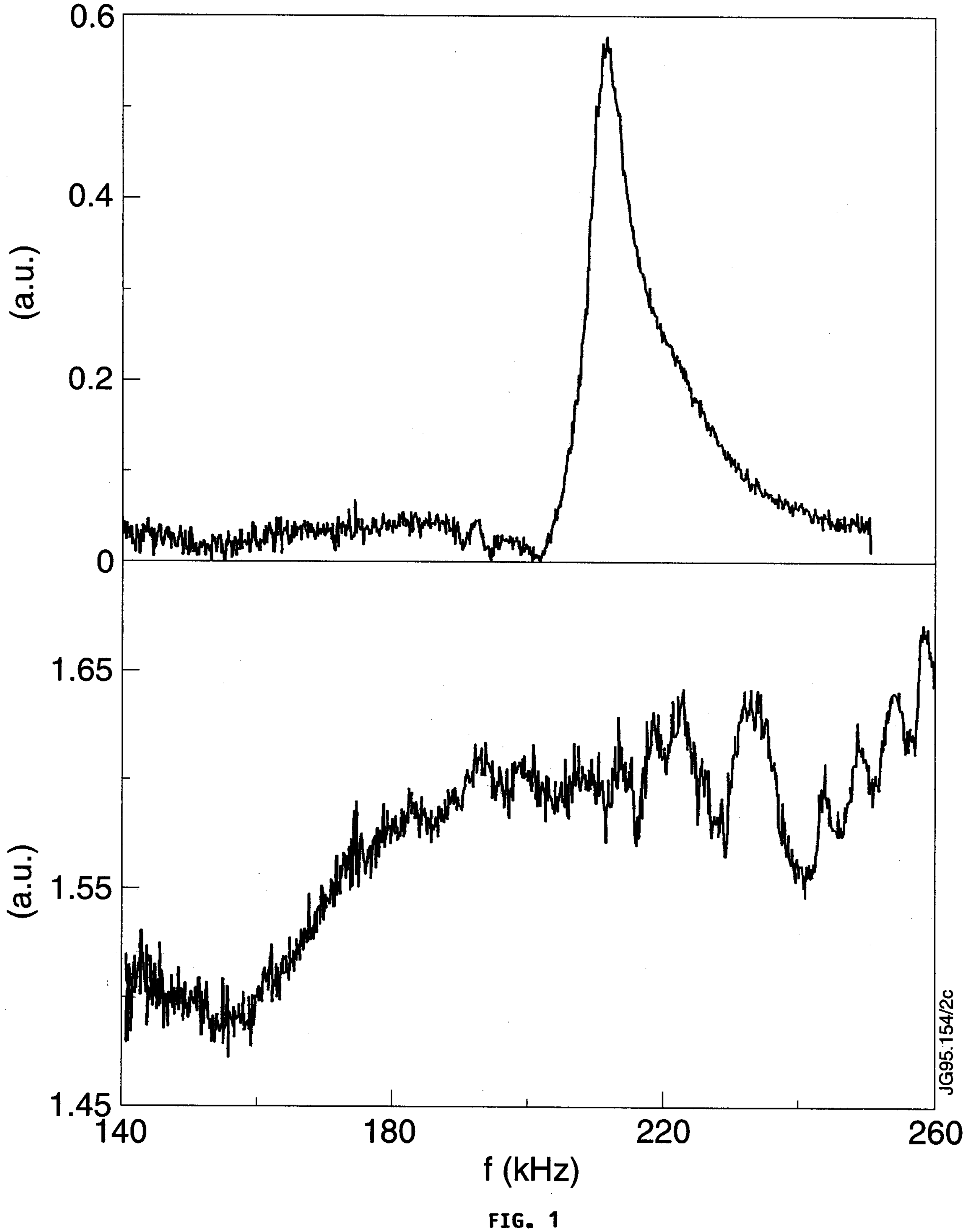


FIG. 1

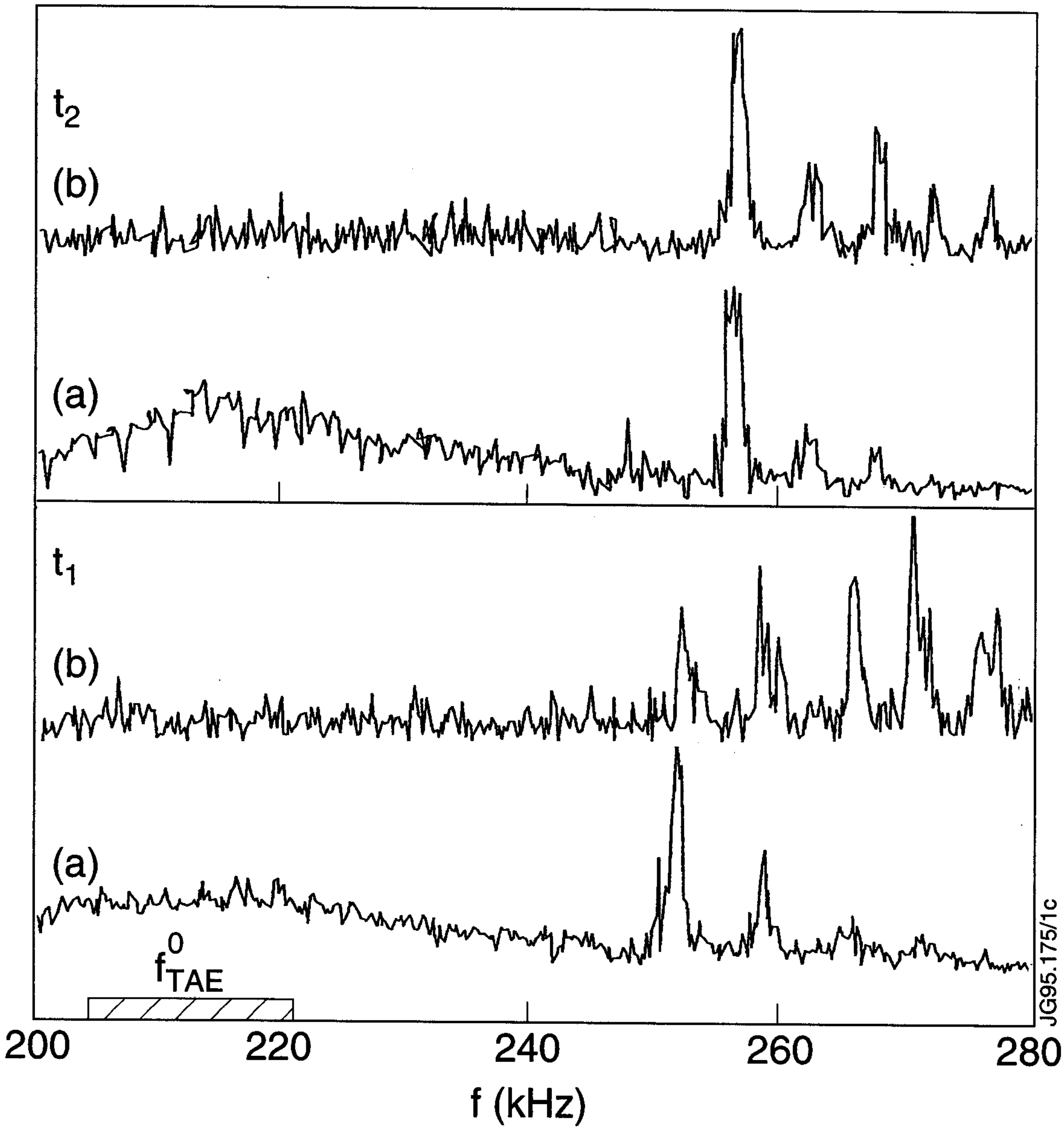


FIG.2

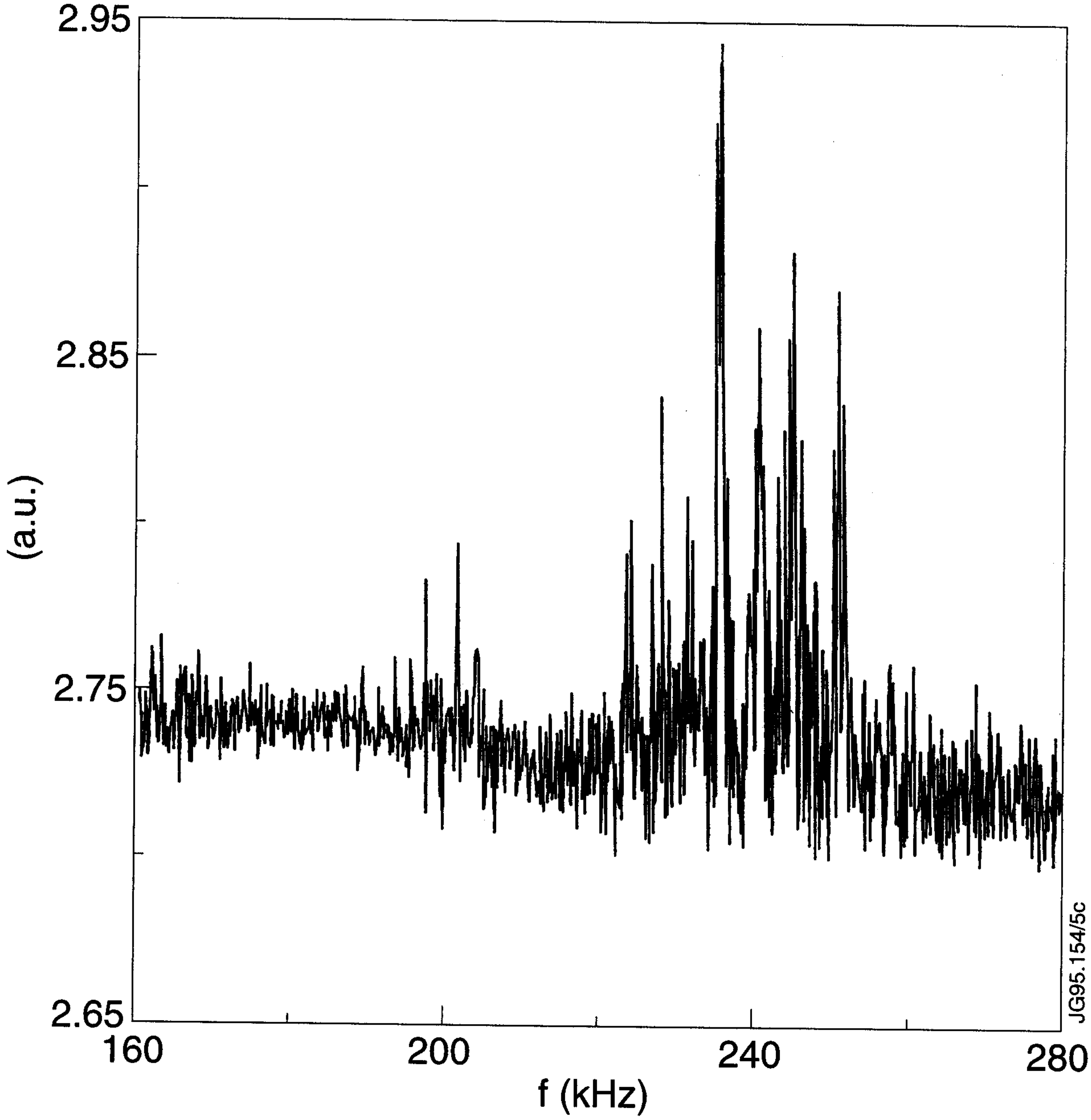
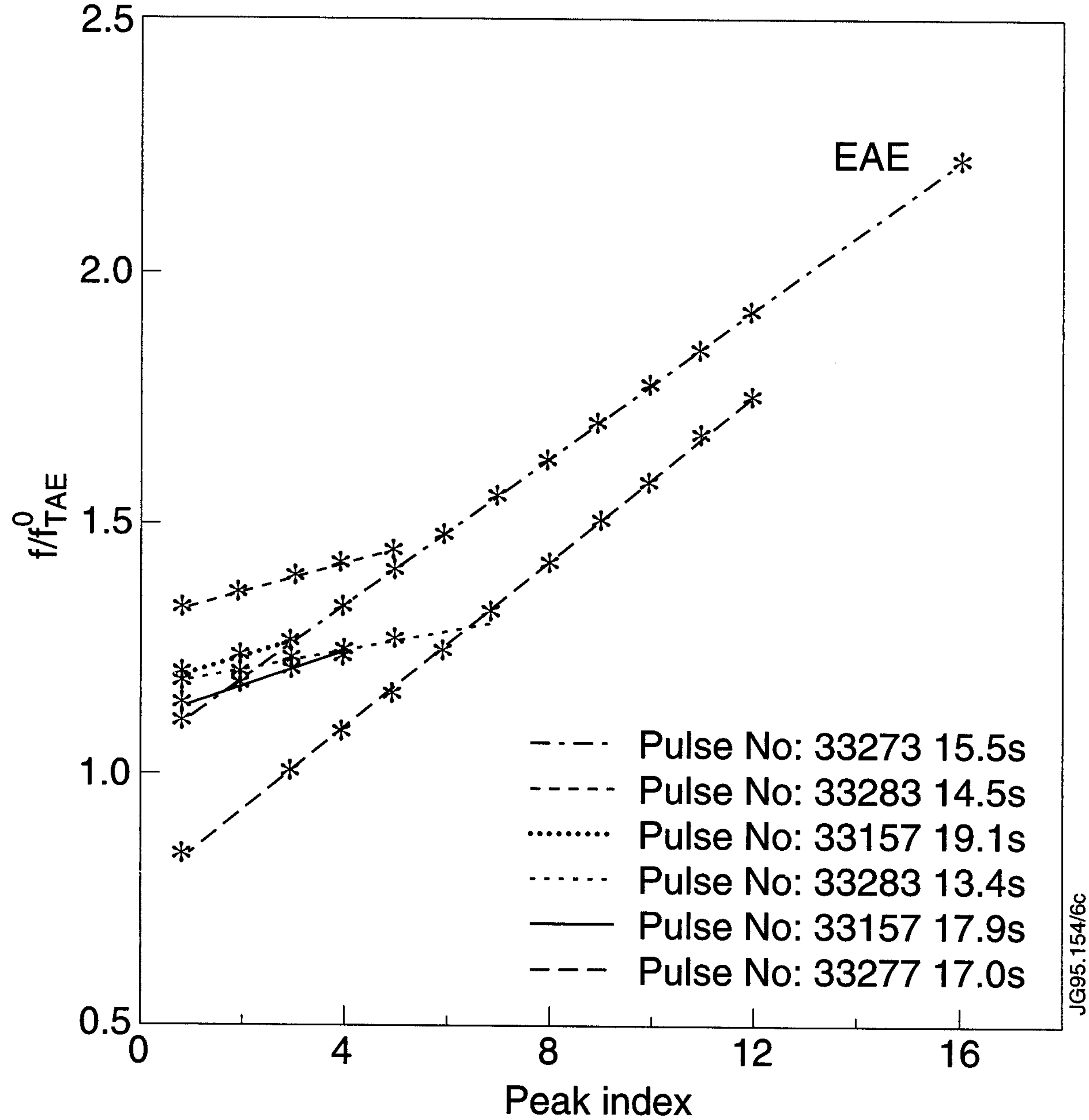
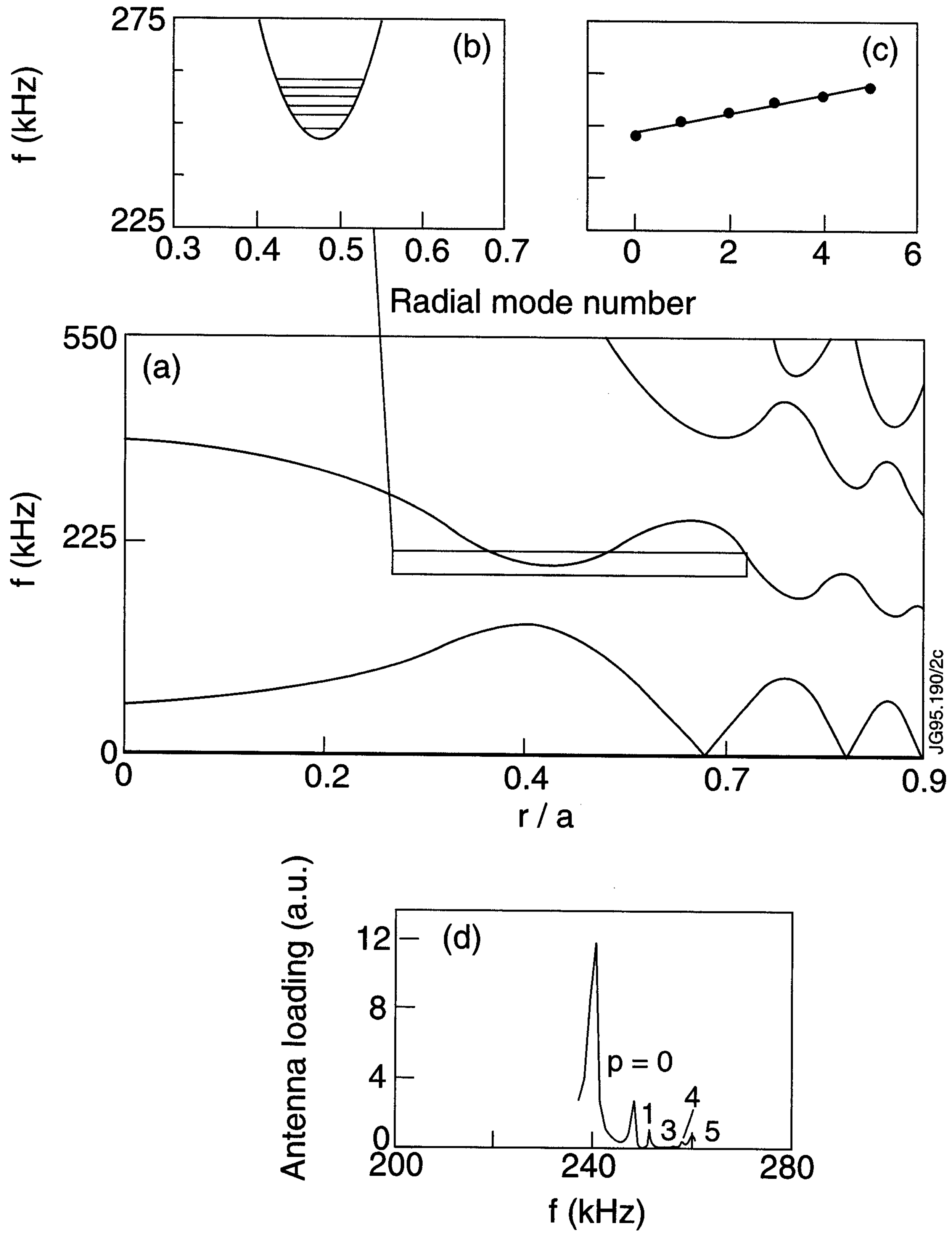


FIG. 3



2.5
2.0
1.5
1.0
0.5
0
4
8
12
16
f/f^0_{TAE}
Peak index
EAE
Pulse No: 33273 15.5s
Pulse No: 33283 14.5s
Pulse No: 33157 19.1s
Pulse No: 33283 13.4s
Pulse No: 33157 17.9s
Pulse No: 33277 17.0s
JG95.154/6c

FIG. 4



275
225
f (kHz)
0.3
0.4
0.5
0.6
0.7
(b)
(c)
0
2
4
6
Radial mode number
550
225
0
f (kHz)
(a)
0
0.2
0.4
0.7
0.9
r / a
JG95.190/2c
Antenna loading (a.u.)
12
8
4
0
(d)
p = 0
1
3
4
5
200
240
280
f (kHz)

FIG. 5

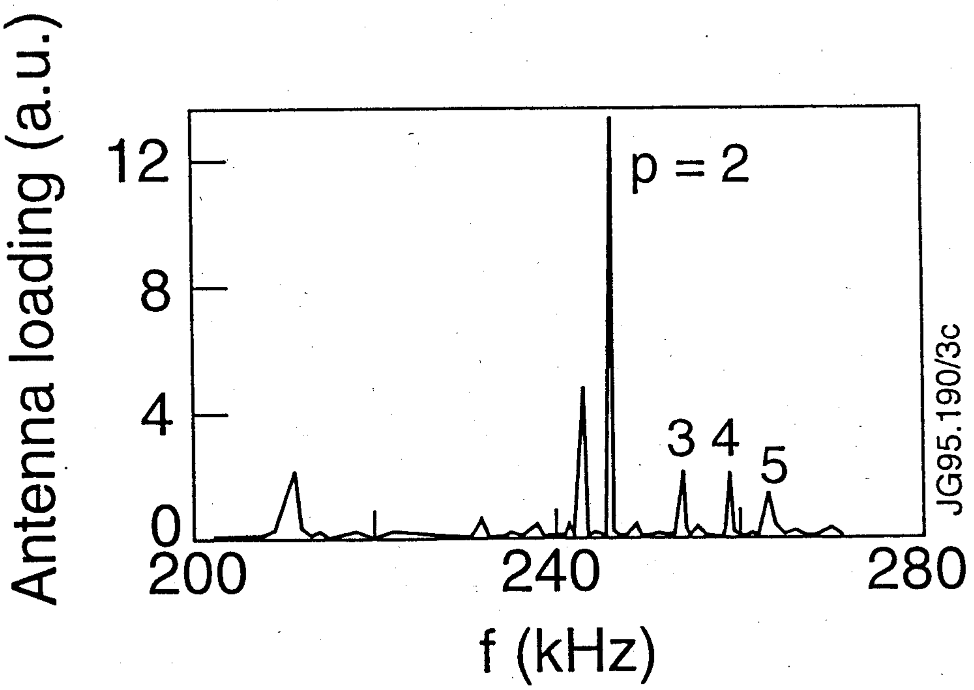


FIG. 6

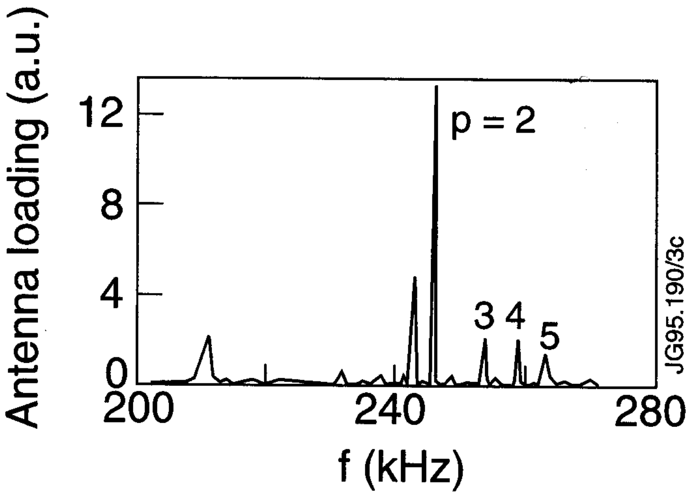


Fig. 6
(maybe to enlarge)