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Measurement of the Damping Rate of n=1 Toroidal Alfvén Eigenmodes as a Function of the Neutral Beam Heating Power and plasma β on JET.

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ABSTRACT

The dependence of the measured damping rate upon the Neutral Beam Heating power (P_{NBI}) and plasma β has been experimentally investigated for n=1 Toroidal Alfvén Eigenmodes (TAEs) in JET limiter plasmas with a monotonic safety factor profile and low edge magnetic shear. The mode frequency is observed to decrease with increasing β, as predicted by various theoretical models. For low $P_{NBI}<3MW$, a single n=1 TAE splits into two modes closely spaced around the expected TAE frequency, and the mode damping rate decreases with increasing β. On the other hand, at higher $P_{NBI}>6MW$, no frequency splitting is observed and there are indications that the mode damping rate increases with increasing β.

One of the major concerns for tokamak plasma experiments aimed at reaching ignition is the stability of the alpha particle population. Slowing-down alpha particles (α s) resonate with Toroidal Alfvén Eigenmodes (TAEs) [1], can drive them unstable up to amplitudes at which they could cause rapid radial transport of α s, thus affecting ignition processes [2].

A dedicated diagnostic system was developed on JET [3] with the aim to study quantitatively the possible damping mechanisms for low-n AEs and provide a reliable extrapolation for ignition plasmas [4]. This system is based on the active excitation of modes in the frequency range $30 \leq f(kHz) \leq 500$ using in-vessel antennas. The plasma response to the driven perturbation is obtained using synchronous detection of magnetic, electron cyclotron emission and reflectometer measurements. This provides a direct, real-time measurement of the mode frequency, damping rate γ/ω and radial structure in different plasma regimes [5,6].

This Letter focuses on the important question of the effect of the plasma beta $\beta = 2\mu_0 p/B^2$ (here p is the plasma pressure) on the damping rate of AEs. Fluid models predict an increase of γ/ω with β for high-n AEs as the mode frequency decreases and the wavefield gets localized in the vicinity of the gap [7]. Gyrokinetic modelling of intermediate n=6 AEs shows that radially localized eigenmodes become more unstable with increasing β, but, as in the fluid case, are stabilized as the wavefield becomes more global and reaches the high magnetic shear region at the plasma edge [8]. In high-β plasmas new families of multiple weakly damped modes have been observed just above a gap in the continuum Alfvén spectrum [9]. The inclusion of kinetic effects for the treatment of AEs has led to the identification of these modes as kinetic AEs (kAEs) above [10] and inside [11] the fluid gap. The experiments presented here are designed to study in detail the dependence of the damping rate for n=1 TAEs on β, with the aim to assess in a more systematic way the validity of the models and the significance of the previous observations.

Two in-vessel antennas are used with opposite phasing to excite preferentially *n=odd* AEs, and current imbalance between the two antennas produces also a small *n=even* component, typically $|n=even/n=odd| \approx 0.1$. Due to the extreme increase of γ/ω for n=1 TAEs with increasing edge magnetic shear $\sigma = (r/q)(dq/dr)$ [6,8,12], a limiter plasma configuration with a low edge magnetic shear is used to discriminate between fluid and gyrokinetic models and diagnose weaker mode conversion

mechanisms in the plasma core. The q-profile is monotonic, with $q(\psi_N=0)\approx0.8\div0.9$ and $q(\psi_N=0.95)\approx2.5$, as obtained using a magnetic reconstruction of the equilibrium constrained by internal motional Stark effect and polarimetry measurements. Here ψ_N is the radial coordinate in units of the normalized poloidal flux, $\psi_N(r)=\psi(r)/\psi(r=a)$. These values are confirmed by the position of the sawtooth inversion radius, as deduced from the electron cyclotron emission measurements of the electron temperature.

To increase β in a controlled way, a ramp in Neutral Beam Injection power (P_{NBI}) is used. In JET the NBI ions are injected at a nominal birth energy $E_b=80keV$ and $E_b=140keV$, with the $^1/_2$ and $^1/_3$ components contributing to approximately 30% of the total number of fast ions injected. The magnetic field and plasma density are carefully chosen so that the NBI-produced fast ions have all a sub-Alfv nic and non-resonant birth parallel velocity (maximum $v_{//NBI}\approx0.21v_A$) to avoid a direct fast ion drive for the n=1 TAEs. The NBI power is increased in 1MW steps at fixed core and edge magnetic shear to isolate experimentally the effect of β and the beam ion population on the mode frequency and damping rate. The duration of each NBI step, $0.5\div1s$, is much longer than the slowing-down time for the NBI ions, $\approx0.1s$. Figure 1 shows the main plasma parameters for Pulse No: 52191, presenting the operating scenario used in this series of experiments.

The mode frequency, amplitude and damping are obtained by fitting the antenna-plasma transfer function $H(\omega)$ for a number of probes with a rational function $H(\omega)=B(i\omega)/A(i\omega)$, where the orders of the polynomials A and B are adjusted so as to minimize the chi-square on the best-fit to $H(\omega)$ [4]. The degree of the denominator is chosen depending on the number of poles in the frequency range of the measurements, corresponding to the number of individual stable modes. Using this technique, two modes closely spaced in frequency are unambiguously resolved when the position of their amplitude peak is separated in frequency by more than the sum of the modes damping, $\Delta\omega_{MIN}=|\omega_1-\omega_2|>\gamma_1+\gamma_2$.

Figure 2 shows the measured mode frequency and damping rate for a n=1 TAE in Pulse No:52191 during the NBI heating phase: we notice here a clear decrease in γ/ω when P_{NBI}, and hence β, increases. Moreover, it is found that the increase in P_{NBI}, up to $P_{NBI}\approx4MW$, causes a single n=1 TAE to split into two modes very closely spaced in frequency, $|\omega_1-\omega_2|/\omega\approx0.05$. Since we are investigating only a very narrow frequency range, $\Delta\omega/\omega_{TAE}\approx0.1$, around the n=1 TAE frequency measured in real-time before the NBI heating phase, the existence of other stable modes outside this narrow frequency range cannot be excluded.

An example of such mode splitting during the NBI phase is shown for Pulse No: 52191 for $P_{NBI}=0 \quad 3MW$ in fig.3a, fig.3b and fig.3c. The mode splitting can be unambiguously inferred by comparing fig.3b with fig.3c, which shows a double-hump structure in the frequency spectrum, not observed in fig.3b. During this phase the edge plasma shape and the q- and magnetic shear profile remain constant, with $q(\psi_N=0)=q_0\approx0.9$, $q(\psi_N=0.95)=q_{95}\approx2.5$, $\sigma_0\approx0.2$, $\sigma_{95}\approx2.5$; the electron temperature is almost constant, $T_{e0}\approx3keV$, whereas the electron density and ion temperature slightly increase, $n_{e0}\approx2.5 \quad 3\times10^{19}m^{-3}$ and $T_{i0}\approx1.5 \quad 2.2keV$.

At higher P_{NBI}, $P_{NBI}>4MW$, the two modes disappear and other stable n=0 GAEs and n=1 TAEs are observed at different frequencies, with much larger damping rate. After the NBI power is stepped down, the single n=1 TAE observed before the beginning of the NBI heating phase is found again at the same frequency and with very similar damping rate. Figure 4 shows the results obtained in a discharge where the NBI power was more rapidly stepped up to $P_{NBI}=10MW$. The damping rate for the n=1 TAE observed at $f_{TAE}\approx110kHz$ initially decreases for $P_{NBI}=0\div4MW$, but remains constant for $P_{NBI}>6MW$. The last few measurements for this mode before the step-up to $P_{NBI}=9MW$, around $t=43.5s$, indicate a small increase in γ/ω, and this feature is observed in the various discharges in the database with a similar P_{NBI} waveform. A n=0 GAE is then detected at $f\approx140kHz$ and $\gamma/\omega\approx3.5\%$ for higher $P_{NBI}\approx7\div10MW$. In other discharges, n=0,1,2 AEs are observed during the high power NBI phase, typically for $P_{NBI}>6MW$, at a frequency higher than that of the mode detected at the beginning of the NBI phase, and with larger $\gamma/\omega\approx5\div10\%$.

To summarize the main features of the measurements, the dependence of γ/ω on the NBI power is different for low $P_{NBI}<3MW$ and high $P_{NBI}>6MW$, but in both cases we observe the predicted decrease in the mode frequency with increasing β [7,8]. In the first case, a single n=1 TAE splits into two modes and the damping rate decreases with increasing β. Conversely, in the second case, only a single n=1 TAE is observed in the frequency spectrum around the n=1 TAE frequency measured at the beginning of the NBI heating phase and its damping rate increases with increasing β.

The experimental results on the mode splitting are not consistent with the prediction of transition from a single TAE to multiple kAEs proposed in Ref.[10]. The mode frequency measured here during the NBI heating phase is very close to that at the center of the toroidal gap, $\omega_{MEAS}\approx\omega_{TAE0}$, where $\omega_{TAE0}=v_A/(2q_{TAE}R_{TAE})$, R_{TAE} is the gap location and $q_{TAE}=(2m+1)/2n$ is the value of the safety factor at the gap location for a TAE with toroidal mode number n and poloidal number m. The models reported in [10] apply only to cases where the mode frequency is very close to that at the top of the toroidal gap, $\omega_{MEAS}\approx\omega_{TAE0}(1+\varepsilon_{TAE})$: here $\varepsilon_{TAE}=2.5*(R_{TAE}-R_0)/R_{TAE}\approx0.3$ is the width of the toroidal gap and R_0 is the position of the magnetic axis. Only in such cases the frequency separation between the two modes observed for $P_{NBI}<4MW$, $\Delta\omega/\omega_{TAE0}\approx0.05$, would be consistent with the predictions of Ref.[10].

On the other hand, the results presented in Ref.[11] show that multiple weakly damped kAEs can appear closely spaced around the n=1 TAE frequency for a fixed background plasma when the ion temperature increases from $T_{i0}=1keV$ to $T_{i0}=3keV$. This prediction could be consistent with the results presented here, but needs to be further refined because (a) the q-profile used in the calculations is much flatter than the experimental one, and (b) more importantly, the measured ion temperature increase is at least a factor 2 smaller than the one assumed in the calculation.

Finally, a possible explanation for the observed $\Delta\omega/\omega_{TAE0}\approx0.05$ can be outlined by considering the effect of beam ions on the dispersion relation for the shear Alfvén wave. Consider here a cold plasma ($T_e=T_i=0$) with no impurity ion species, where $\Omega_j=Z_jeB/m_jc$ and $\omega_{pj}=\sqrt{4\pi n_jZ_j^2e^2/m_j}$ are respectively the cyclotron and plasma frequency for the species j. By adding to the cold plasma

dielectric tensor elements a low-density, $n_b/n_i <<1$, sub-Alfvénic, $v_0<<v_A$, population of fast ions moving along the direction of the magnetic field, two solutions of the wave dispersion relation are obtained perturbatively in cylindrical geometry around the Alfvén frequency as

$$\left(k_\parallel^2 c^2 - \omega^2 \frac{\omega_{pi}^2}{\Omega_i^2}\right)^2 = \left(\frac{\omega_{pi}^2}{\Omega_i} \frac{n_b}{n_i} k_\parallel v_0\right)^2 \qquad \omega_{1,2} = \omega_A \sqrt{\left|1 \pm \frac{n_b}{n_i} \frac{v_b}{v_A} \frac{\Omega_i}{\omega_A}\right|} = \omega_A \pm \omega_b \qquad (1)$$

A fast ion beam moving in the direction of the toroidal magnetic field could therefore give rise to two neighboring solutions of the shear Alfvén wave dispersion relation, as observed in the experiments presented here. To estimate quantitatively the separation between the two roots of Eq.1, we take for the representative beam ion parallel velocity the square root of the parallel component of the total energy of the calculated slowing down beam ion distribution function, $W_{b//}=n_b m_b v_0^2/2$, giving $v_0/v_A \approx 0.05$. Using this value, the frequency separation between the two roots of Eq.1 is $\Delta\omega/\omega_A \approx 0.05 \div 0.1$, consistent with the measurements. Conversely, for much lower beam ion density and mean parallel velocity, the frequency separation between the two roots of Eq.1 becomes too small compared to the resolution on the measurement of the mode frequency.

In summary, the linear stability of n=1 TAEs has been experimentally studied as a function of the NBI heating power and β in plasmas characterized by a monotonic q-profile and low edge magnetic shear. The prediction by both fluid and gyrokinetic models that the mode frequency decreases for increasing β is confirmed. However, the predictions from the fluid models of an increase in γ/ω with β are challenged by the data presented here, which show that γ/ω decreases for increasing β and a single n=1 TAE splits into two modes closely spaced in frequency for $P_{NBI}<3MW$. The observed decrease in γ/ω for a n=1 global TAE could be qualitatively consistent with the predictions from gyrokinetic models for core-localized n=6 kAEs in plasmas with a low edge magnetic shear [11]. The measurements presented here can provide a tool for a detailed quantitative investigation of the various models used to predict the instability thresholds for global AEs in future burning plasma experiments such as ITER.

ACKNOWLEDGEMENTS

REFERENCES.

[1]. C.Z.Cheng, L.Chen, M.S.Chance, *Ann. Phys.* **161** (1985), 21.

[2]. K.L.Wong, *Plasma Phys. Controlled Fusion* **41** (1999) R1.

[3]. J.Wesson, *Tokamaks*, 2nd edition (Oxford Science Publication, Oxford, UK, 1997), p.581.

[4]. A.Fasoli et al., *Phys. Rev. Lett.* **75** (1995), 645.

[5]. A.Fasoli et al., *Phys. Plasmas* **7** (2000), 1816.

[6]. D.Testa and A.Fasoli, *Nucl. Fusion* **41** (2001), 809.

[7]. L.Villard, S.Brunner, J.Vaclavik, *Nucl. Fusion* **35** (1995), 1173; S.Sharapov et al., *Nucl. Fusion* **39** (1999), 373; G.Fu et al, *Phys. Plasmas* **2** (1995), 1029.

[8]. A.Jaun, A.Fasoli, J.Vaclavik, L.Villard, *Nucl. Fusion* **40** (2000) 1343.

[9]. A.Fasoli et al., *Phys. Rev. Lett.* **76** (1996), 1067.

[10]. J.Candy and M.Rosenbluth, *Phys. Plasmas* **1** (1994), 356; H.Berk, R.Mett and D.Lindberg, *Phys. Fluids* **B5** (1993), 3969; B.N.Breizman and S.Sharapov, *Plasma Phys. Control. Fusion* 37 (1995), 1057.

[11]. A.Jaun et al., *Plasma Phys. Control. Fusion* **39** (1997), 549.

[12]. A.Jaun, A.Fasoli and W.Heidbrink, *Phys. Plasmas* **5** (1998), 2952; A.Fasoli, A.Jaun, and D.Testa, *Phys. Lett.* **A265** (2000), 288.

Pulse No: 52191
Plasma parameters

Pulse No: 52191
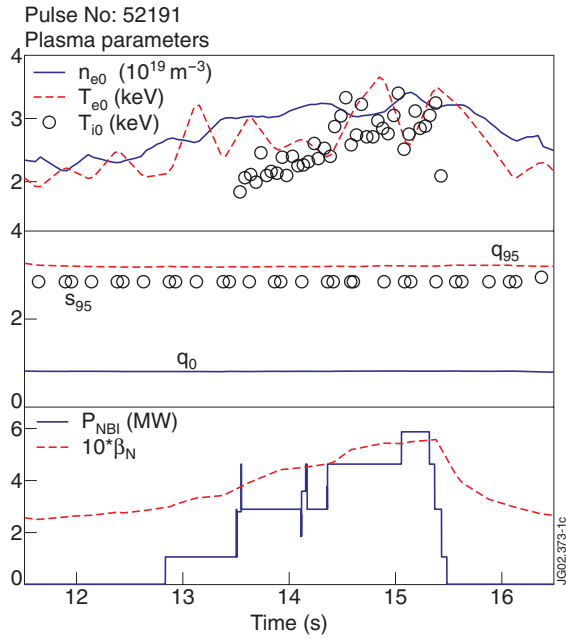n = 1 TAE frequency and damping rate

Figure 1: The main plasma parameters during the NBI heating phase of Pulse No: 52191, representing the typical operating scenario for the experiments reported here.
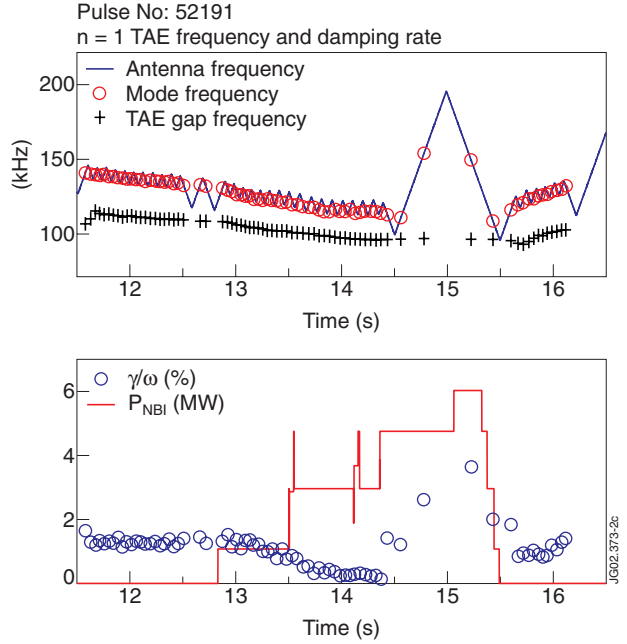
Figure 2: The measured damping rate for a n=1 TAE during the NBI heating phase of Pulse No: 52191: note that both the mode frequency and damping rate decreases at the beginning of the NBI heating phase. For P_{NBI}>2MW two distinct modes appear in the frequency spectrum, but only the evolution of one mode is plotted here for clarity.

Pulse No. 52191
$|\delta B/B|$ (12.466< = time (s) < = 12.5955)

Frequency = 132.3kHz, γ/ω = 1.4%

Pulse No. 52191
$|\delta B/B|$ (13.4939< = time (s) < = 13.5671)

Frequency = 119.2kHz, γ/ω = 0.87%

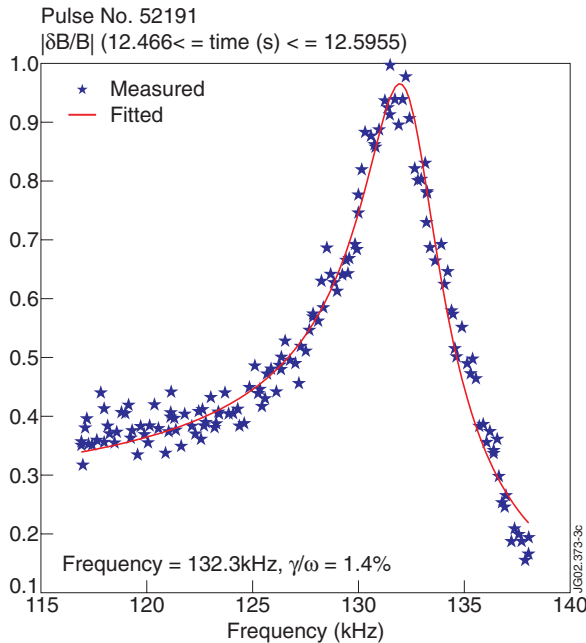*Figure 3(a): The n=1 TAE frequency spectrum immediately before the beginning of the NBI heating phase of Pulse No: 52191: here one single mode is found.*
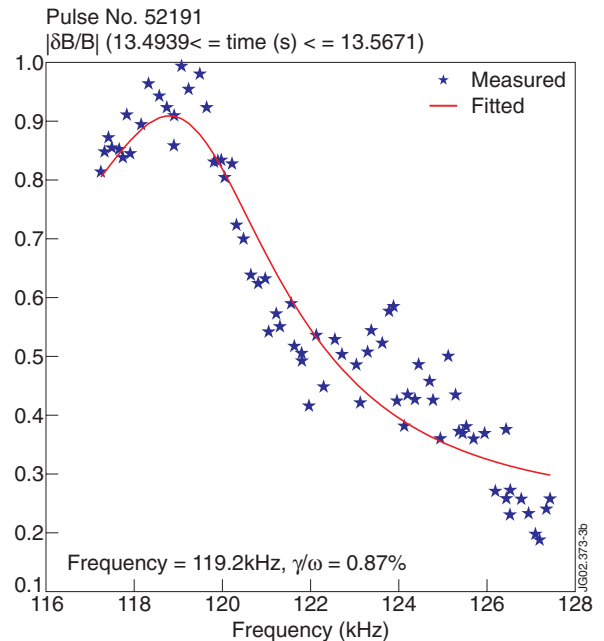
Figure 3(b): The n=1 TAE frequency spectrum at the beginning of the NBI heating phase of Pulse No: 52191, for P_{NBI}=1MW: here still one single mode is found.
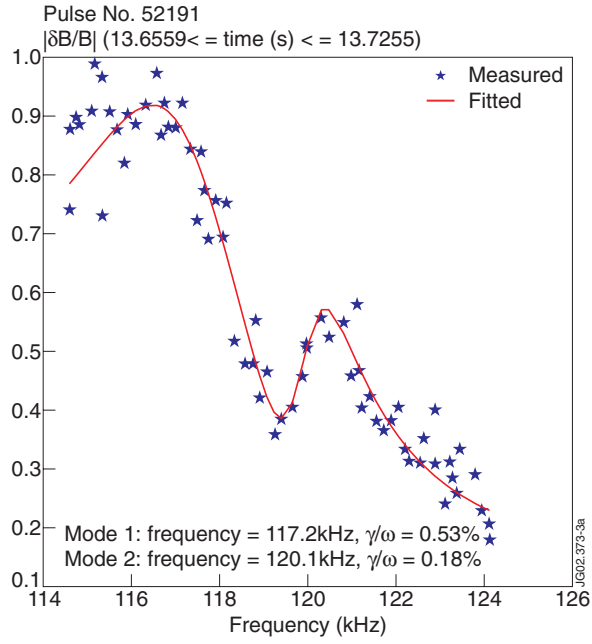
Figure 3(c): The n=1 TAE frequency spectrum during the NBI heating phase of Pulse No: 52191, for P_{NBI}=3MW: here two modes are clearly visible in the spectrum.
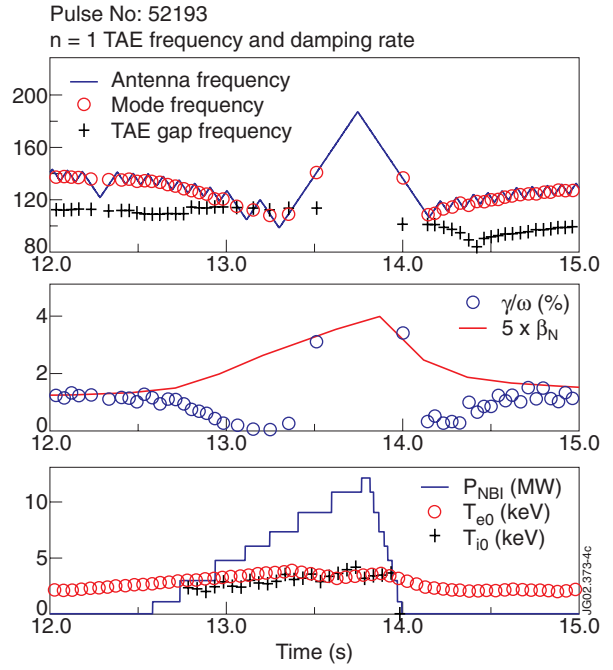
Figure 4: The measured frequency and damping rate for a n=1 TAE in Pulse No: 52193 during the NBI phase: we notice that during a rapid ramp-up of P_{NBI}, γ/ω initially decreases and then remains constant for P_{NBI}>6MW. The n=1 TAE observed at the beginning of the NBI phase is lost and a different n=0 GAE is observed at higher frequency in the TAE frequency range.