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Experimental Study of the Stability of Alfvén Eigenmodes on JET

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ABSTRACT.

Over the last few years, experiments have been performed on JET to study the dependence of the AE stability limits on the main plasma parameters in different operating scenarios. The measurements are compared with theoretical models with the aim of improving the prediction capabilities for burning plasma experiments, such as ITER. An increase in the edge magnetic shear provides a significant stabilising contribution for AEs in plasmas characterised by a monotonic q-profile. Conversely, with non-monotonic q-profiles and Internal Transport Barriers, multiple weakly damped modes exist in the Alfvén frequency range even in the presence of a high edge magnetic shear, with possible negative implications for the AE stability in ITER. The dependence of the frequency and damping rate of n=1 TAEs on the bulk plasma β was also analysed using NBI heating in limiter plasmas. The mode frequency decreases for increasing β, in agreement with fluid and gyrokinetic predictions. Conversely, contrary to fluid predictions for intermediate and high-n TAEs, for low NBI powers weobserve a splitting in the n=1 TAE frequency spectrum, accompanied with a reduction of the mode damping rate. The dependence of the damping rate for n=1 TAEs on the Larmor radius ρ_i has been investigated for plasmas characterised by a low magnetic shear in the core. In these plasmas the coupling between AEs and kinetic Alfvén waves is predicted to contribute significantly to the total damping rate for n=1 TAEs. This mechanism is accounted for by the radiative damping model in the NOVA-K code, and is a strong function of ρ_i. Whereas NOVA-K reproduces accurately the measured mode frequency, it is found that the calculated damping rate is too small to account for the measured value under these experimental conditions.

1. INTRODUCTION

One of the main issues on the way to a magnetic fusion reactor is the stability of plasma collective modes. Fast particle driven modes, such as Alfvén Eigenmodes (AEs), may cause losses of fast ions, such as fusion born alpha particles in DT plasmas, significantly degrading the plasma performance. The JET tokamak combines the capability of producing reactor-relevant plasmas characterised by significant populations of fast particles with a unique active mode excitation technique [1]. Information on the AE stability limits and its dependence on background plasma parameters can be inferred in different plasma operating scenarios. This paper presents recent data obtained with the AE active diagnostic system on JET. The measurements are compared with various theoretical models, with the aim of improving the prediction capabilities for future burning plasma experiments such as ITER.

2. THE EFFECT OF THE PLASMA SHAPE ON THE TAE STABILITY IN THE CONVENTIONAL AND ADVANCED TOKAMAK SCENARIO

The dependence of the AE damping rate on the edge plasma shape has been systematically investigated in the limiter phase of a number of discharges with a monotonic q-profile. In agreement with the predictions of the gyrokinetic code PENN [2,3], it was found that the increase in the edge magnetic shear, elongation and triangularity contributes to increasing the damping rate γ/ω for global, antenna-driven, stable n=1 TAEs [4].

Figures 1 and 2 show the results of recent experiments aimed at measuring the AE excitation threshold, using the drive provided by resonant NBI ions with $\upsilon_{||NBI} \approx \upsilon_A$, for $n = 3 \div 10$ TAEs, as a function of the edge magnetic shear. These modes are expected to be more easily destabilised by the fast particles in ITER than $n = 1 \div 2$ TAEs. We compare plasmas with low and high edge magnetic shear, in limiter and X-point configuration, respectively. For similar background plasma conditions, one needs 30% less NBI power ($P_{NBI} = 5.3$MW compared to $P_{NBI} = 8$MW), and further away from the resonance ($\upsilon_{||NBI} \approx 0.8\,\upsilon_A$ compared to $\upsilon_{||NBI} \approx 0.95\,\upsilon_A$ due to a different plasma density) to destabilise TAEs with intermediate n's in plasmas with low edge magnetic shear than with high edge magnetic shear. On the other hand, for plasmas with similar low edge magnetic shear and monotonic q-profile, $P_{NBI} = 5.3$MW is not sufficient to destabilise $n = 0 \div 2$ TAEs for $\upsilon_{||NBI} \approx 0.8\,\upsilon_A$. This result confirms earlier predictions and measurements on the stabilising effect of edge magnetic shear for TAEs in plasmas with monotonic q-profiles. As expected, this effect appears to be weaker for radially localised $n = 5 \div 7$ TAEs than for global $n = 1 \div 2$ TAEs.

In X-point plasmas with high edge magnetic shear but non-monotonic q-profile and a core transport barrier, produced in the JET Reverse Shear scenario, a lower NBI power, $P_{NBI} = 4.5$MW, is sufficient to destabilise $n = 3 \div 5$ modes in the AE frequency range. Energy well below the MeV range (which is needed to destabilise TAEs in conventional scenarios), with $\upsilon_{||NBI} \approx 0.3\,\upsilon_A$, seem to be sufficient [5]. This could be due to the coupling between kinetic and drift Alfvén waves in plasmas with a deeply non-monotonic q-profile, a high value of q0 and negative magnetic shear in the core [6].

3. THE EFFECT OF THE NBI HEATING POWER AND PLASMA • ON THE FREQUENCY AND DAMPING RATE OF N=1 TAES

One important question to address to accurately predict the TAE stability in ITER is the effect of the plasma normalised pressure, $\beta = 2\mu_0 p/B^2$, on the mode frequency and damping rate [7]. Figure 3 shows the measured mode frequency and γ/ω for a n = 1 TAE in Pulse No: 52191 during the NBI heating phase. As predicted by fluid [8] and gyrokinetic models [9], the mode frequency decreases with increasing β. We also notice a clear decrease in the damping rate when P_{NBI}, hence β, increases, up to $P_{NBI} = 3 \div 4$MW. For these levels of NBI power no major changes are observed in the plasma profiles (q, pressure, density and temperature), which maintain the characteristic L-mode shape.

Moreover, we observe a second n = 1 TAE for increasing P_{NBI}, up to $P_{NBI} \approx 4$MW. These two modes are very closely spaced in frequency, $|\omega_1 - \omega_2|/\,\omega_{TAE} \approx 0.05$, where ω_{TAE} is the centre of the TAE gap. Figures 4a and 4b show an example of this observation during the NBI phase of Pulse No:52191, for $P_{NBI} = 0 \rightarrow 3$MW. Fluid models predict an increase of γ/ω with β for high-n AEs as the mode frequency decreases and the wavefield gets localised close to the gap. Therefore the observed decrease in γ/ω for increasing β is not consistent with these predictions. Similarly, the appearance of two n=1 TAEs very closely spaced in frequency for $2<P_{NBI}(MW)<4$ is not consistent with the prediction of a transition from a single TAE to multiple kTAEs proposed in Ref.[10].

The mode frequency measured during the NBI heating phase is very close to that at the centre of the toroidal gap, whereas the models reported in [10] could reproduce the observed splitting only if the mode frequency was close to that at the top of the toroidal gap. Only in such cases would the frequency separation between the two modes observed for P_{NBI} <4MW, 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 $T_{i0} = 1$keV to $T_{i0} = 3$keV. This prediction could be consistent with the results presented here, but needs to be further refined because the q-profile used in the calculations is much flatter than the experimental one, and, more importantly, the measured ion temperature increase is at least a factor of two smaller than that assumed in the calculation. The effect of beam ions on the dispersion relation for the shear Alfvén wave could give rise to two modes closely spaced in frequency [7]. By introducing in the cold plasma dielectric tensor a low-density, $n_b/n_i \ll 1$, sub-Alfvénic, $\upsilon_b \ll \upsilon_A$, population of fast ions moving along the direction of the magnetic field, two solutions of the Alfvén wave dispersion relation are obtained pertubatively around the Alfvén frequency as $\omega_{1,2} = \omega_A(1 \pm n_b\, \upsilon_b\, \Omega_i/n_i\, \upsilon_A\, \omega_A)^{1/2} = \omega_A \pm \omega_b$, with $\omega_b / \omega_A \approx 0.05$.

4. TEST OF THE RADIATIVE DAMPING MODEL FOR N=1 TAES

The dependence of γ/ω for n=1 TAEs on the ion Larmor radius ρ_i has been investigated in plasmas with low magnetic shear to assess the significance of a damping mechanism resulting from the coupling between TAEs and kinetic Alfvén waves [12]. This mechanism is modelled as radiative damping in the kinetic code NOVA-K [13]. The radiative damping rate γ/ω_{RAD} is predicted to depend on ρ_i through the parameter $\lambda_{GAP} = 4(2/5)^{3/2}\,(m\sigma\rho_i/r)(R/r)^{3/2}\,(3/4+T_e/T_i)^{1/2}$, evaluated at the gap position [13,14]. In the limit of small magnetic shear, $\sigma \ll \sigma\sqrt{8}/\pi$, we have $\gamma/\omega_{RAD} = (\pi^2/8)\varepsilon_m\, \sigma_{GAP}{}^2 \exp(-\pi^3\, \sigma_{GAP}{}^2 /2^{7/2}\, \lambda_{GAP})$. Here $\varepsilon_m = 5r_{GAP}/2R_{GAP}$, and R_{GAP} is the mode radial position along the major radius. In addition to the radiative damping, γ/ω_{RAD}, NOVA-K includes the Landau damping due to the trapped electrons, γ/ω_{ELE}, but does not include continuum damping [15] nor a variety of toroidal mode conversion mechanisms, which require a gyrokinetic modelling of the global wavefield [3].

Figure 5 shows the measured and computed damping rates for a m/n=2/1 TAE during the ohmic phase of a JET limiter discharge. The reduction of the mode frequency with the toroidal magnetic field is well reproduced by the NOVA-K calculation. Conversely, the computed damping rate (mainly from electron Landau damping) is about a factor 20 smaller than the measured one, with the radiative damping being even smaller.

Figure 6 show an overview of the data considered for this comparison at fixed plasma shape and magnetic shear, $q_0 \approx 0.8$, $2.5 \le q_{95} \le 3$ and $0.2 \le \sigma_{GAP} \le 0.3$. The database covers a wide range in the electron temperature and density at the gap location, respectively $1.6 \le T_{eGAP}(keV) \le 2.5$ and $1.5 \le n_{eGAP}(10^{19}\ m^{-3}) \le 2.9$, which is the origin for the observed scatter in the data. We notice the decrease in $\gamma/\omega_{MEAS} \approx 1/\lambda_{GAP}$ for $2.5 \leq \lambda_{GAP}(10^{-2}) \leq 3.5$, whereas γ/ω_{MEAS} becomes practically independent on λ_{GAP} at higher λ_{GAP}, $3.5 \leq \lambda_{GAP}(10^{-2}) \leq 5$. Further work is needed to resolve the discrepancy between the theoretical damping models analysed here and the experimental results. To improve the modelling of the low-n TAE stability limits in JET, the missing damping mechanism needs to be identified for the experimental conditions reported here. To this aim, detailed comparisons with other models could be useful. Second, according to the NOVA-K predictions, the radiative damping is expected to increase with the toroidal mode number and the ion Larmor radius. Thus the radiative damping model needs to be further tested in these experimental conditions.

5. NEW HIGH-N TAE ANTENNAS

The present JET Saddle Coil system can only excite low-n AEs. This system has been unique in providing large amounts of data on the frequency, damping rates and mode structure of AEs in a variety of plasma conditions. As discussed in this presentation such data is important to understand the physics of wave-particle interaction in the AE range of frequencies, and specifically to benchmark theoretical predictions for the stability of low-n AEs in ITER. However, AEs with intermediate to high mode numbers are also expected to be important in ITER. Building on the existing system, a new set of antennas to drive AEs with intermediate-n (up to n ≈ 10÷15) is being designed for future installation on JET.

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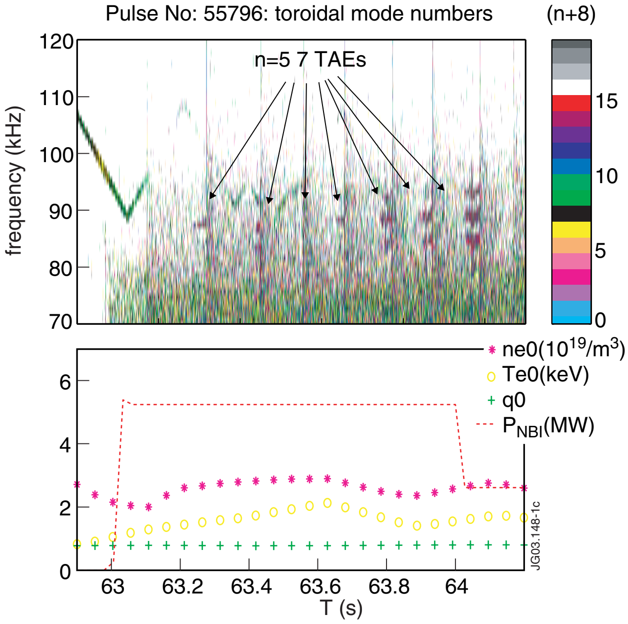

Figure 1: Limiter plasma with monotonic q- profile: $n = 5 \div 7$ TAEs become unstable at $P_{NBI} = 5.3MW$, with $|\upsilon_{||NBI}| \approx 0.8\ \upsilon_A$.

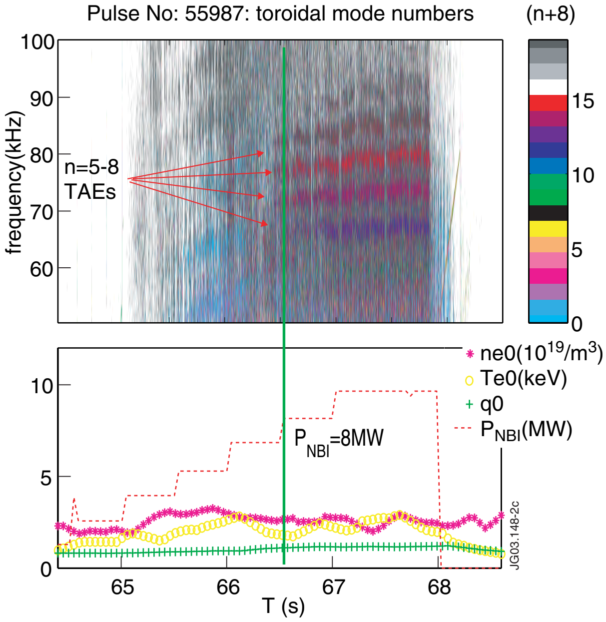

Figure 2: X-point plasma with monotonic q-profile: $n = 5 \div 8$ TAEs become unstable at $P_{NBI} = 8MW$, with $|\upsilon_{||NBI}| \approx 0.95\ \upsilon_A$.

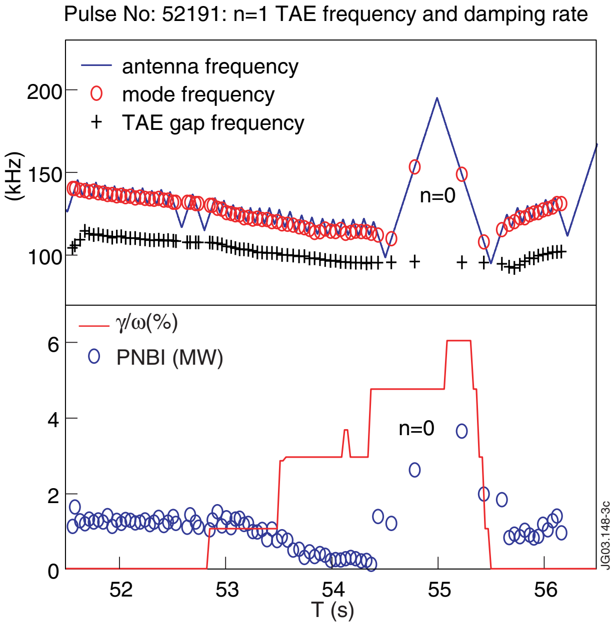

Figure 3: The measured damping rate for a n=1 TAE during the NBI heating phase of Pulse No:52191. For P_{NBI}>2MW two distinct modes appear in the frequency spectrum, but only the evolution of one mode is plotted here for clarity.

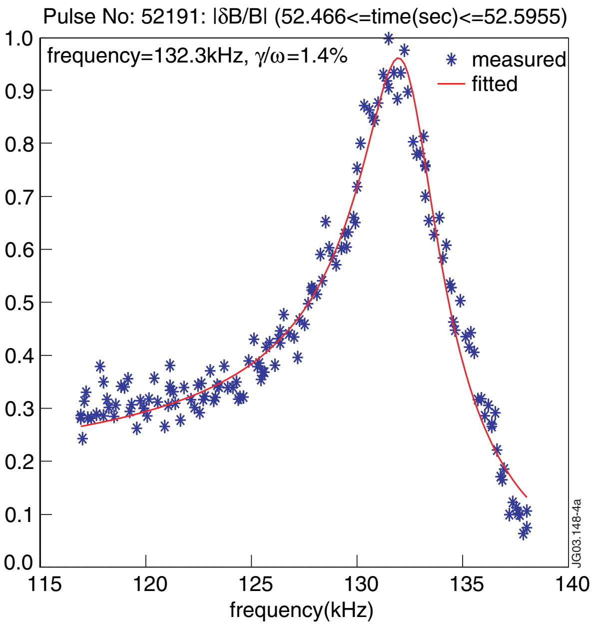

Figure 4a: "The n=1 TAE frequency spectrum before the beginning of the NBI heating phase of Pulse No: 52191: here one single mode is found.

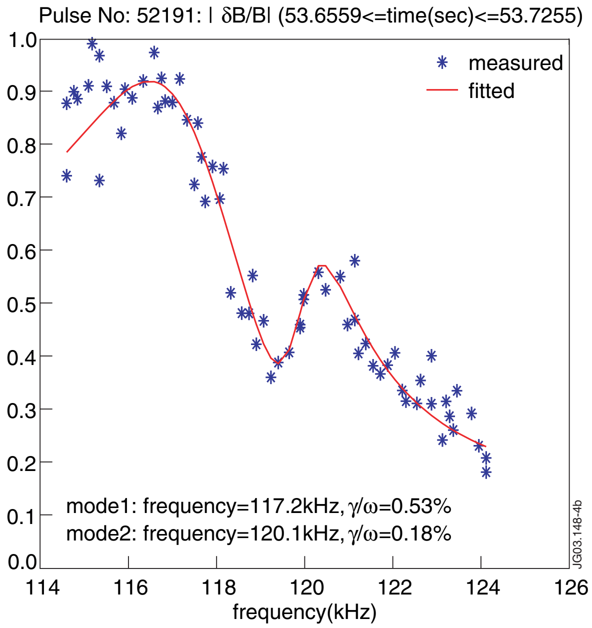

Figure 4b: "The n=1 TAE frequency spectrum during in Pulse No: 52191 for P_{NBI} *= 3MW: here two modes are clearly visible in the spectrum.*

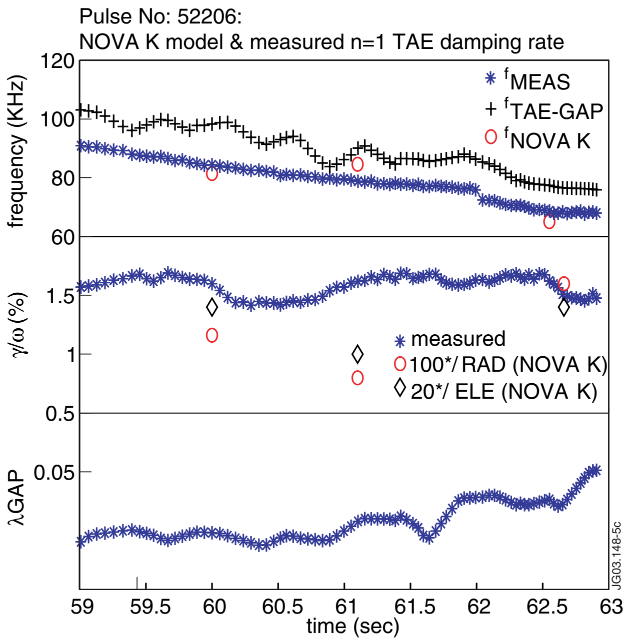

Figure 5: The measured frequency and damping rate for a n=1 TAE during the ohmic heating phase of Pulse No: 52206, compared with the radiative and trapped electron contribution, as computed by NOVA-K.

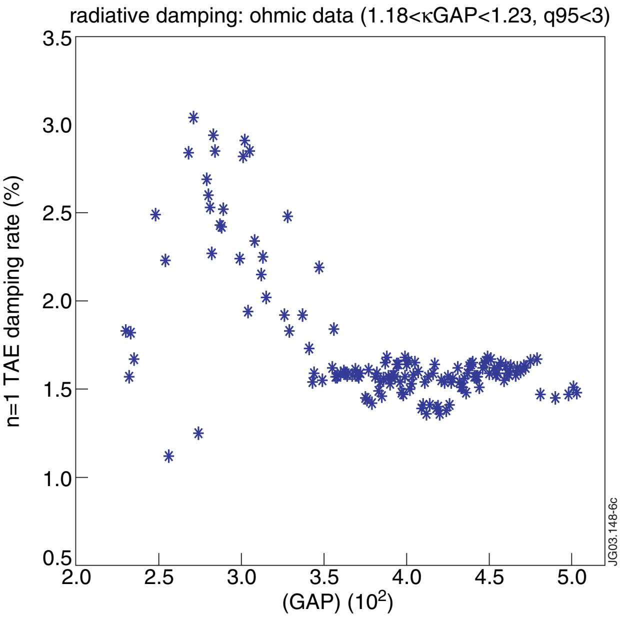

Figure 6: The dependence of the measured γ/ω *for n=1 TAEs upon* λ_{GAP} *in the ohmic phase of the five discharges considered here:* $\gamma/\omega \approx 1/\lambda$ *for* $2.5 \leq (10^{-2}) \leq 3.5$*, whereas it becomes practically independent on* λ *at higher* λ*,* $3.5 \leq \lambda\,(10^{-2}) \leq 5$*.*