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ABSTRACT.

The damping rate of the n=1 TAE mode in Ohmic-heated JET plasmas has been measured and compared with the prediction of the kinetic NOVA-K code, which includes electron and ion Landau damping of the global shear-Alfvén wave field, collisional damping, and radiative damping. It was found that the calculated damping rate is too small to account for the measured value under these experimental conditions.

INTRODUCTION.

A major issue in future burning plasma experiments will be the control of the stability of the alpha particle population (α's). As resonant interaction between the α's and Toroidal Alfvén Eigenmodes (TAEs) [1] can cause radial redistribution of the α's and may lead to net particle losses [2], large experimental and theoretical efforts are undertaken to assess the TAE stability in reactor relevant conditions.

This Letter focuses on damping mechanisms of n=1 TAEs. The understanding of damping mechanisms and their scaling is important for validating theoretical models and predictions of TAE stability in larger tokamak experiments such as ITER. Direct measurements of the mode frequency and damping rate γ/ω, obtained with the JET dedicated AE diagnostic system [3,4], are compared with the predictions of the kinetic code NOVA-K [5]. The experiment was originally designed to test the NOVA-K model for the radiative damping, which results from the coupling between MHD TAE mode and kinetic Alfvén waves. For the parameters and profiles realised in the experiments reported here, however, the radiative damping is not the main damping mechanism and is much too small to account for the measured values. The dominant damping mechanism in the NOVA-K calculation is the electron Landau damping which is still a factor 20 smaller than the measured value.

The experiments presented here investigate the dependence of the damping rate for n=1 TAEs on the ion Larmor radius ρ_i, with the aim of assessing the validity and relevance of the radiative damping model. The radiative damping rate, γ/ω_{RAD}, is a strong function of the ion Larmor radius through the kinetic parameter λ [5,6]:

$$\lambda = 4\,\frac{m\sigma}{r\varepsilon_m^{3/2}}\left(\frac{3}{4}+\frac{T_e}{T_i}\right)^{1/2}\rho_i. \tag{1}$$

Here σ =(r/q)dq/dr is the magnetic shear, $R = R_0 + r$ is the major radius (R_0 is the position of the magnetic axis and r the radial coordinate along the minor radius), q(r) is the safety factor profile, T_e and T_i are the electron and ion temperature, respectively. All the experimental quantities entering the definition of λ, hence the calculation of γ/ω_{RAD}, are computed at the gap position r_{TAE} for the TAE with toroidal mode n and poloidal mode numbers (m, m+1). The parameter $\varepsilon_m = 5r_{TAE}/2R_{TAE}$ is a measure of the frequency width of the toroidal gap. In the limit of small magnetic shear $\sigma << \sqrt{8}/\pi$, the expression for γ/ω_{RAD} reduces to [5,6]:

$$\left(\frac{\gamma}{\omega}\right)_{RAD} = \frac{\pi^2}{8}\,\varepsilon_m\,\sigma^2 \times \exp\left(-\frac{\pi^3\sigma^2}{2^{7/2}\,\lambda}\right). \qquad (2)$$

Two in-vessel antennas are used with opposite phasing to preferentially excite n=1 AEs. Due to the extreme increase of γ/ω for n=1 TAEs with increasing edge magnetic shear, elongation and triangularity, discovered in previous experiments [4], a limiter plasma configuration with low magnetic shear at the gap position, $\sigma_{GAP} \approx 0.25 < \sqrt{8}/\pi$, is used. Similarly, the elongation and triangularity are very low, $1.18 \leq \kappa_{GAP} \leq 1.23$ and $0.01 \leq \delta_{GAP} \leq 0.03$ respectively, and are held approximately constant during the limiter phase of the discharge. The q-profile is monotonic, with $q_0=q(\psi_N = 0) \approx 0.75 \div 0.85$ and $q_{95} = q(\psi_N = 0.95) \approx 2.65 \div 3.3$, as obtained using a magnetic reconstruction of the equilibrium constrained by the internal motional Stark effect (MSE) and polarimetry measurements. Here ψ_N is the radial coordinate in units of the normalised 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 T_e. The electron density (n_e) and temperature radial profiles show a typical L-mode shape throughout the evolution of the discharge. The edge density and temperature are very low, of the order of $n_{e95}/n_{e0} \approx T_{e95}/T_{e0} \approx 0.05$. Diagnostic Neutral Beam Injection (NBI) heating up to a power PNBI=3MW is used for the MSE and charge-exchange measurements of the q- and T_i profile. However, due to the effect of the NBI ions on the n=1 TAE spectrum [7], the NBI heating phase of the discharge is not considered here. The ion temperature is not directly measured during the ohmic phase of the discharge, thus it is inferred from the measured T_e and neutron rate profile.

Figure 1 shows the main plasma parameters during the ohmic limiter phase of Pulse No: 52206, representing the typical operating scenario for the experiments reported here. To be able to discriminate between the radiative and other damping mechanisms, the magnetic field and plasma current are ramped down at fixed q_{95} and edge shape in order to change • i, hence • , affecting as little as possible the other background plasma parameters.

Figure 2 shows the measured, γ/ω_{MEAS}, and computed damping rate for a n=1 TAE during the ohmic phase of Pulse No: 52206. The gap position for n=1 TAEs is located around $\psi_{N,GAP} \approx 0.45$, and the gap width $\Delta_{GAP} \approx \varepsilon_m r_{TAE}/m$ [8] is of the order of $\Delta_{GAP} \approx 10$cm. In addition to the radiative damping, γ/ω_{RAD}, NOVA-K also includes the electron Landau damping γ/ω_{ELE} and collisional damping due to trapped electrons. The mode frequency decreases due to decrease in the magnetic field, and there is a very good agreement between the measurements and the NOVA-K calculation. However, 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 3 shows the measured damping rate γ/ω_{MEAS} versus the normalised Larmor radius at the gap location $\rho_{*iGAP} = \rho_{*iGAP}/a$ (where a is the plasma minor radius) for the database collected during the ohmic limiter phase of the five discharges considered in this work. The selection presented here is obtained with $2.65 \le q_{95} \le 3$ and $0.2 \le \sigma_{GAP} \le 0.3$, and represents approximately 70% of the complete data set, the remaining 30% including data obtained during the NBI heating phase and at higher q_{95} and σ_{GAP}. The database covers a large range in the density and temperature at the gap location, respectively $1 \le n_{eGAP}(10^{19}\ m^{-3}) \le 3$ and $0.8 \le T_{eGAP}(keV) \le 2.5$, which, together with the variation in q_{95} and σ_{GAP}, is the origin for the observed scatter in the data.

It is interesting to note that the main trend of the data indicates that the measured damping rate is larger for smaller gyroradius. This is opposite to the scaling of the radiative damping and other simple kinetic models. The experimental results show an approximate dependence $\gamma/\omega_{MEAS} \approx 1/\rho_{*iGAP}$ for $2.5 \le \rho_{*iGAP}(10^{-3}) \le 3.2$, whereas at higher ρ_{*iGAP}, $3.2 \le \rho_{*iGAP}(10^{-3}) \le 5$, γ/ω_{MEAS} becomes practically independent on ρ_{*iGAP}. A similar trend is also obtained with respect to λ_{GAP}. We have calculated the radiative damping rate using Eq.(2) for all these data points and the value is about 20-50 times smaller than γ/ω_{MEAS}, albeit increasing strongly with ρ_{*iGAP} and λ_{GAP}. This confirms the NOVA-K results shown in Fig.2 for three of these cases.

Further work is needed to resolve the discrepancy between the theoretical damping models examined in this Letter and the experimental results. The NOVA-K model has been tested on a number of other experiments, for instance giving a good estimate of the stability threshold for α-driven TAEs in TFTR [5]. Thus, to improve the understanding and modelling of the low-n TAE stability limits in JET, the missing damping mechanism needs to be identified for the experimental conditions reported in this Letter. To this aim, detailed comparisons with other models could be useful. As an example, for one timeslice in the NOVA-K calculation the frequency intersects with the Alfvén continuum near the edge, due to the very low edge density in these experiments. In such cases the continuum damping [9] should be included in the calculation of the global fluid wavefield. Toroidal mode conversion provides for other mechanisms, which have previously been found in agreement with the measurements under similar conditions [10]. Furthermore, NOVA-K predicts the radiative damping to increase with the toroidal mode number and the ion Larmor radius. Thus the model needs to be further tested for TAEs with higher toroidal mode numbers in experimental conditions where a larger ρ_I is achieved. A new set of high-n TAE antennas is being designed for installation on JET, with the aim to provide the data required to validate code predictions for these modes.

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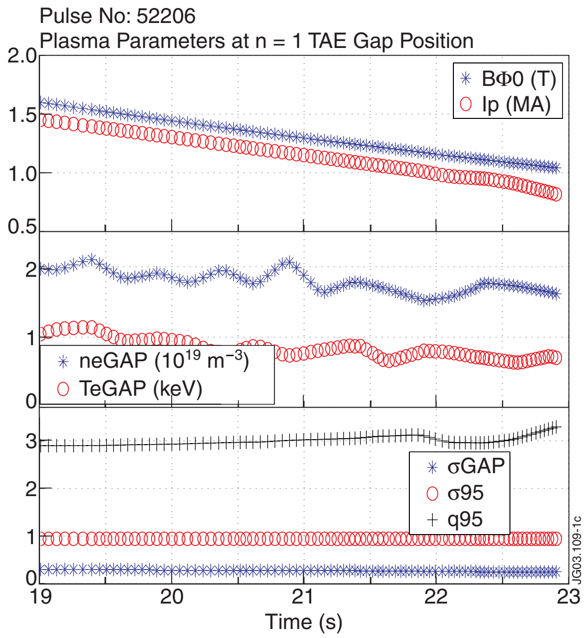

Figure 1: The main plasma parameters during the ramp-down phase of the magnetic field for Pulse No: 52206, representing the typical operating scenario for the experiments reported here. The data are evaluated at the gap position for the n=1 TAE, $\psi_{N,GAP} \approx 0.45$.

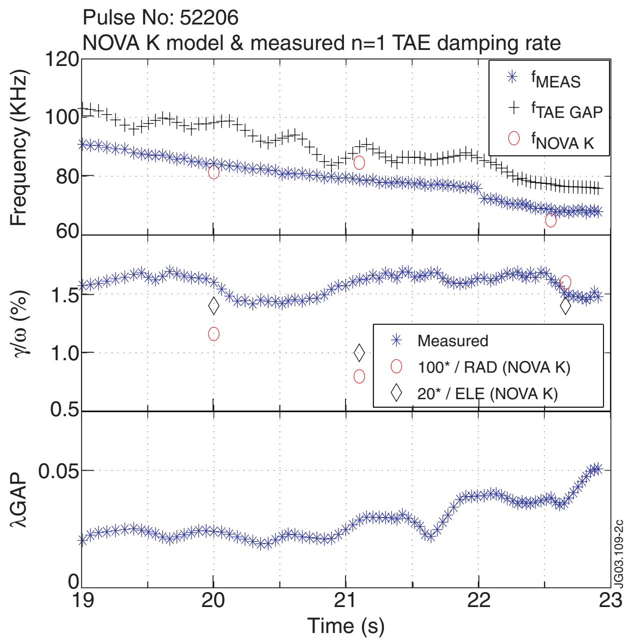

Figure 2: The measured frequency and damping rate for a n=1 TAE during the ohmic heating phase of Pulse No: 52206, compared with the radiative and trapped electron contribution, as computed by NOVA-K. Note the large multiplicative factor between the measured damping rate and the NOVA-K results.

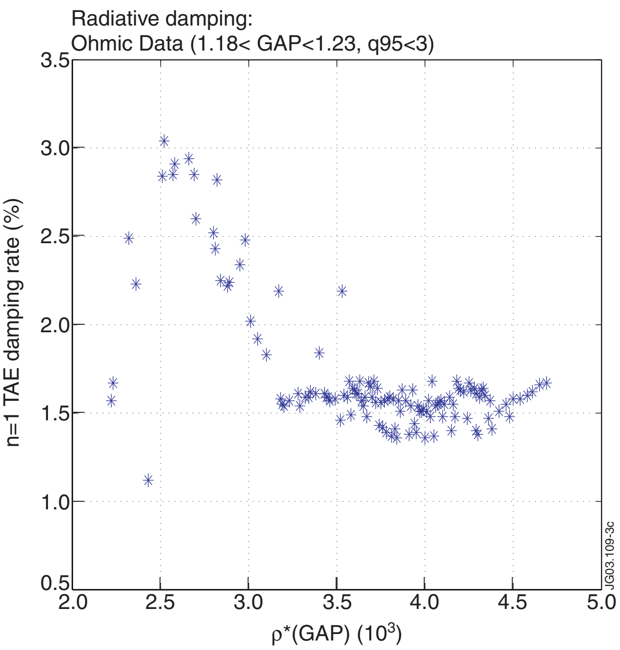

Figure 3: The dependence of the measured damping rate for n=1 TAEs upon the normalised Larmor radius at the gap position ρ_{*iGAP} during the ohmic limiter phase of the five discharges considered here, which have a very similar q-profile within the uncertainty on the equilibrium reconstruction. Note the decrease in $\gamma/\omega_{MEAS} \approx 1/\rho_{*iGAP}$ for $2.5 \le \rho_{*iGAP} (10^{-3}) \le 3.2$, whereas γ/ω_{MEAS} becomes practically independent on ρ_{*iGAP} for $3.2 \le \rho_{*iGAP} (10^{-3}) \le 5$.