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The Effect of Plasma Shaping on the Damping of low-n Alfvén Eigenmodes in JET Tokamak Plasmas

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ABSTRACT

The effect of plasma shaping on the damping of radially extended Alfvén Eigenmodes (AEs) is investigated experimentally during the limiter phase of JET plasma pulses. The AE damping rate is observed to increase with increasing elongation, triangularity and edge magnetic shear. These parameters could therefore be used to control the AE stability in real-time.
Classification scheme: D0, Te.

One of the major concerns for deuterium-tritium burning plasma experiments is the stability of the alpha particle population. Fusion generated alpha particles (α's) resonate with Alfvén waves as they slow down by colliding with electrons and thermal ions. Alfvén waves can therefore be driven unstable and reach amplitudes at which they cause radial transport of α's, affecting fusion energy production and ignition processes [1]. In a tokamak, the coupling of different poloidal harmonics in the Alfvén wave spectrum produces global wave fields known as Alfvén Eigenmodes (AEs) [2]. The stability properties of AEs are therefore of importance for the design of next step devices with significant amounts of alpha particle heating. Of particular interest is the case of radially extended AEs, which, if driven to large enough amplitudes, could cause radial redistribution of particles over the entire plasma cross-section and lead to net losses.

To identify and quantify the possible damping mechanisms for low toroidal mode number AEs in different plasma regimes, an active diagnostic system was developed at JET [3]. This system, based on the measurement of the plasma response to perturbations driven by in-vessel Saddle Coil antennas, provides a direct measurement of the damping rate of stable AEs.

Various mechanisms have been proposed for the damping of AEs in tokamak plasmas. The wave energy can be absorbed via Landau damping on electrons or ions [4], either directly [5,6,7] or through mode conversion to kinetic Alfvén waves [8,9,10]. This latter mechanism is included in the gyrokinetic code PENN, and accounts for the measured AE damping rates on the

JET tokamak [11,12]. These comparisons with theory indicate that strong damping can occur in regions of large magnetic shear, $\sigma=(r/q)(dq/dr)$, at the plasma edge and suggest a strong sensitivity to the plasma shape. This has motivated the systematic experimental analysis of AE damping rates as a function of the plasma shape and edge magnetic shear reported in this Letter.

After a brief overview of the measurement technique and experimental set-up, we present the measured AE damping rates for a series of steady-state limiter discharges with varying plasma shape and edge magnetic shear. The results are discussed in light of the possibility of real-time feedback control of stable AEs approaching their marginal stability boundary.

The four JET Saddle Coils are used as in-vessel antennas to drive n=0 global AEs (GAEs) and n=1 and n=2 toroidicity induced AEs (TAEs). The maximum antenna current and voltage used for the AE excitation experiments are typically of the order of 10A and 700V, corresponding to a very small antenna-driven magnetic field, $|\delta B/B|<10^{-5}$. The plasma response to the driven perturbation is measured using synchronous detection of signals from magnetic coils [3], allowing the reconstruction of the AE toroidal structure. A 1kHz-clock digital control system, the Alfvén Eigenmode Local Manager (AELM), is used to control the AE exciter in real time. The AELM sweeps linearly the antenna frequency around an initial guess for the AE resonance, usually taken at the center of the toroidal gap, $f_{TAE}=\upsilon_A/4\pi q_G R_G$. Here the Alfvén velocity υ_A is computed using the magnetic field and central plasma density measured in real-time, R_G and q_G are respectively the major radius and safety factor at the center of the toroidal gap. The frequency sweep is selected to cover the expected width of the toroidal gap, allowing for uncertainties in the initial guess for f_{TAE}: $f_{AELM}=f_{TAE}\pm(50\div100)kHz$.

The AELM is used to detect and track in real-time the individual resonances corresponding to antenna-driven, stable plasma modes. A fit of the complex antenna/plasma transfer function is then applied [3,11], to obtain the mode frequency, $f_{AE}=Re(\omega_{FIT})/2\pi$, and damping rate, $(\gamma/\omega)_{AE}=Im(\omega_{FIT})/Re(\omega_{FIT})$, as well as the mode amplitude at the different probe locations, with a typical time resolution of the order of 20ms. Typically, when the plasma approaches the X-point phase and the edge magnetic shear is increased, the damping of the antenna-driven low-n AEs becomes too large ($\gamma/\omega>5\%$) for a resonance to be recognized in real-time [10,13].

The AE damping measurements reported in this Letter were performed in a series of experiments with similar background plasma conditions, aimed at studying the effect of the elongation and triangularity on the energy and particle confinement time [14]. Our database includes 79 different discharges. The limiter phase of these discharges is characterized by pure ohmic heating. The q-profile is monotonic, with positive shear throughout the poloidal cross-section, and it has fully relaxed at the time of the AE measurements. The central safety factor is $q_0\approx0.9$, confirmed by the position of the sawtooth inversion radius, and reaches $q_{95}\approx4$ at 95% of the poloidal flux, as computed with the EFIT equilibrium reconstruction code. The typical plasma parameters are central and volume-averaged electron density $n_{e0}\approx2.5\times10^{19}m^{-3}$ and $<n_e>\approx2\times10^{19}m^{-3}$, central and volume-averaged electron temperature $T_{e0}\approx2.5keV$ and $<T_e>\approx1keV$

(the ion temperature was not measured during the limiter phase of these discharges), vacuum magnetic field $B_{\phi 0}=2.2T$ and plasma current $I_p=2.6\ MA$. The elongation on-axis is varied in the range $1.05 \leq \kappa_0 \leq 1.45$, and the edge elongation is in the range $1.1 \leq \kappa_{95} \leq 1.8$. The triangularity above and below the plasma mid-plane are respectively $0.05 \leq \delta_{UP}$ and $\delta_{LOW} \leq 0.45$. The magnetic shear at the q=1 surface is $\sigma_0 \approx 1$, and the edge shear is in the range $5 \leq \sigma_{95} \leq 15$.

Figure 1 shows typical examples of the measurements obtained during these experiments. For JET pulse #51158, shown in Fig.1a (left), two antennas were energized with opposite phase: two radially extended n=1 AEs were detected, whose frequencies are respectively close to the top and bottom of the TAE gap. On the other hand, for JET pulse #51159, shown in Fig.1b (right), the two antennas were energized with the same phase, and only one global n=0 GAE was measured. Both discharges are in quasi-steady conditions during the AE damping measurements in terms of the background plasma parameters, such as the electron density and temperature, the plasma current and the magnetic field. Thus we conclude that the variations in the AE damping rates are solely due to the change in the plasma shape. The measurements are obtained during the limiter phase of the discharge, and the X-point is formed around t=14s.

In Fig.1 f_{TAE} is the AE frequency computed in real-time using $R_G=3m$ and $q_G=1.5$, f_{SC} is the antenna frequency being swept around the expected f_{TAE} and f_{MEAS} is the measured mode frequency. For both plasma pulses we notice a clear increase in γ/ω as the edge shape is modified during the approach to the X-point phase. These measurements allow us to separate the effect of the edge shear from that of the elongation and triangularity. Although it is not possible to hold σ_{95} completely fixed while increasing κ_{95} and δ, we notice that a clear increase in the damping rate occurs when δ_{UP} is increased, around t=10.2s. On the other hand, during this phase, the edge shear is only very slowly increasing.

Figure 2 summarizes the results obtained in these experiments. The data are taken at almost fixed $q_{95} \approx 4$, $q_0 \approx 0.9$ and $\sigma_0 \approx 1$. Figure 2a (left) shows the dependence of the measured damping rate separately on the elongation (averaged over $0.08 < \delta_{LOW} \approx \delta_{UP} < 0.12$) and triangularity (averaged over $1.1 < \kappa_0 < 1.2$ and $1.2 < \kappa_{95} < 1.3$) for the n=1 TAE and the n=0 GAE. We notice that when averaging over low values of the plasma elongation, the AE damping rate increases approximately linearly with the triangularity and the edge magnetic shear. Conversely, when averaging over low values of the plasma triangularity, the AE damping rate shows a sharp increase for a small variation in the elongation around $\kappa_{95} \approx 1.5$ and $\kappa_0 \approx 1.35$. Figure 2b (right) shows the overall dependence: here $\kappa(r/a=0.5)$ is given by a parabolic fit $\kappa=\kappa_0+\alpha(r/a)^2$, with $\alpha=(\kappa_{95}-\kappa_0)/(0.95)^2$, and $<\delta>=(\delta_{UP}+\delta_{LOW})/2$. The measurements show a strong effect of the edge plasma shape, as determined by the elongation and triangularity, on the AE damping rate: the effect is comparable for the n=0 GAE and the n=1 TAE.

The strong sensitivity of the AE damping rates upon the edge shape parameters may lead to a method to control the stability of fast ions resonating with AE global wave fields. For this, it is necessary to obtain in real-time a reliable signal providing the distance from the marginal stability boundary for the modes. We have developed a simple algorithm to obtain $(\gamma/\omega)_{REAL-TIME}$ from the width of the frequency sweep, using the phase inversion characteristic of a stable, antenna-driven, plasma resonance. Figure 3 shows $(\gamma/\omega)_{REAL-TIME}$ as a function of $(\gamma/\omega)_{FIT}$, the value obtained from the fit of the antenna-plasma transfer function. These data were obtained in different limiter discharges, including various discharges with Ion Cyclotron Resonance Frequency heating and Neutral Beam Injection heating. We notice an almost exact one-to-one correspondence: $(\gamma/\omega)_{REAL-TIME} \approx (\gamma/\omega)_{FIT}$. Based on a command generated from this real-time measurement of AE damping rate, the coils used to shape the plasma could be energized with a typical time response of the order of 20ms, thus achieving a real-time control of radially extended, fast ion driven AE instabilities.

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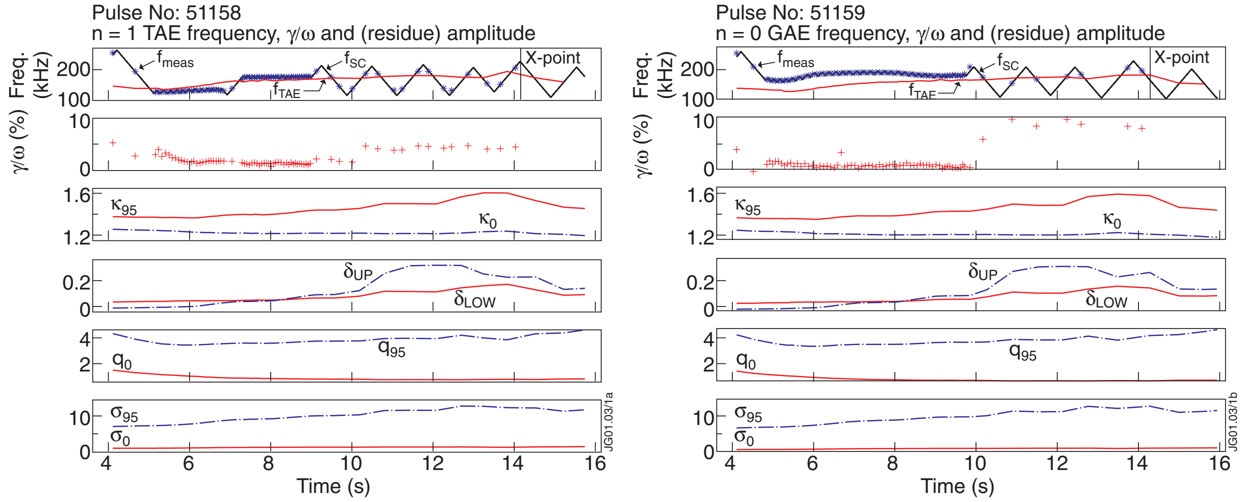

Fig.1: Measurement of the AE damping rate during the ohmic limiter phase of JET pulse #51158 (left) and #51159 (right). We notice that for #51158 two n=1 TAEs were present in the toroidal gap, with $f_{AE}=\omega/2\pi=125$*kHz and* $f_{AE}=170$*kHz, with almost identical damping rate, whereas for #51159 only one n=0 GAE was observed, with* $f_{AE}=160\rightarrow180$*kHz. The X-point phase starts at t=14s: the measured damping rate shows a sharp increase when the edge shaping is modified to prepare for the X-point formation. We notice that the edge shear slowly increases, while the sharp variation in* γ/ω *is closely related to the increase in* δ_{UP}.

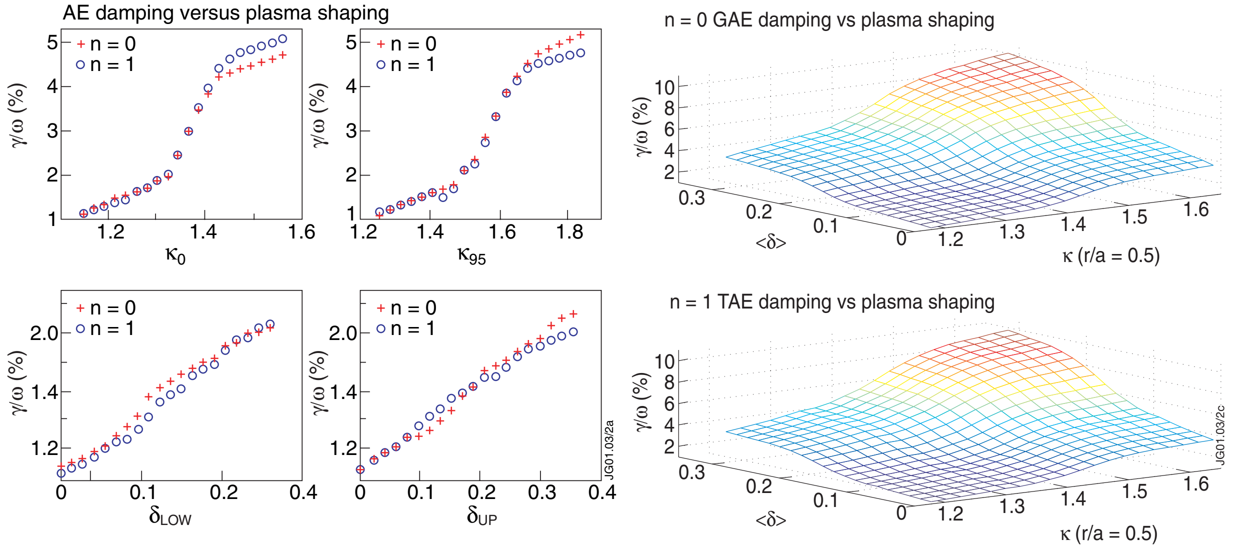

Fig.2: Variation of the measured AE damping rates as a function of the elongation (at almost constant $0.08<\delta_{LOW}\approx\delta_{UP}<0.12$*) and triangularity (at* $1.1<\kappa_0<1.2$ *and* $1.2<\kappa_{95}<1.3$*), for* $q_{95}\approx4$, $q_0\approx0.9$ *and* $\sigma_0\approx1$. *Here* $<\delta>=(\delta_{UP}+\delta_{LOW})/2$ *and* $\kappa(r/a=0.5)$ *is given by the parabolic fit* $\kappa=\kappa_0+\alpha(r/a)^2$. *The data are shown for n=0 GAEs and n=1 TAEs during the ohmic limiter phase of JET plasma pulses. We notice a sharp variation in* γ/ω *as a function of the elongation around* $\kappa_{95}\approx1.5$ *and* $\kappa_0\approx1.35$*, whereas* γ/ω *varies approximately linearly with the triangularity.*

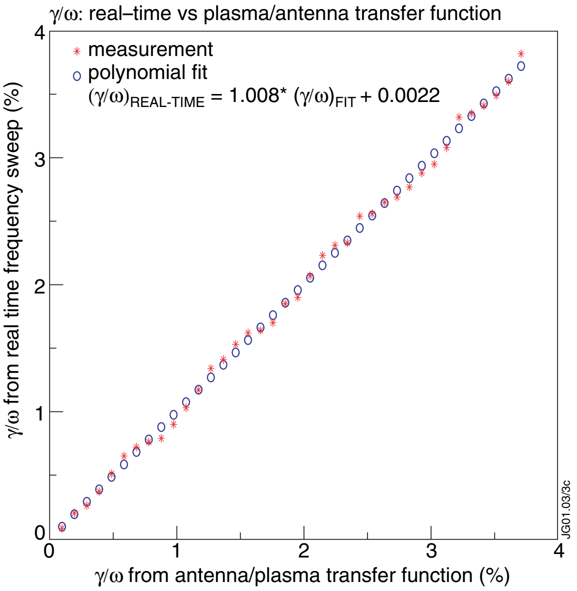

Fig.3: The real-time measurement of the AE damping rate $(\gamma/\omega)_{\text{REAL-TIME}}$ *is compared with the result obtained using the fit of the antenna-plasma transfer function,* $(\gamma/\omega)_{\text{FIT}}$*, showing an almost exact one-to-one scaling.*