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Real-Time Measurements of Damping Rates and Instability Limits for MHD Modes on the JET Tokamak

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1. Introduction

The linear stability properties of plasma collective modes is investigated in the JET tokamak using external excitation, focusing on the possibility of developing control tools for optimising the performance of burning plasmas based on the mode measurements. Both the high frequency range, $80 \leq f(kHz) \leq 400$, typical of Alfvén Eigenmodes (AEs), and the low frequency range, $5 \leq f(kHz) \leq 50$, in which internal kinks, tearing and infernal modes lie, are explored [1]. Modes in both classes can have a strong impact on the behaviour of burning plasmas. The high frequency modes can be driven by a significant population of high energy ions, such as those produced by Ion Cyclotron Resonance Heating (ICRH) or fusion born alpha particles (α's) in DT plasmas. Due to the resonant exchange of energy with α's, AEs are relevant to burn control issues. The low frequency modes are important for the performance of advanced tokamak scenarios such as the JET Optimised Shear (OS) regime [2].

2. Experimental method

The JET saddle coils are used as external antennas to drive and detect stable MHD modes in both frequency ranges, and evaluate their damping rates. Magnetic perturbations of the order $|\delta B/B|<10^{-5}$ are applied to the plasma, low enough to avoid generating particle transport or non-linear wave effects [3]. The modes are detected synchronously by magnetic probes located at the plasma edge, to measure the mode structure, the frequency and damping rate [3]. The Alfvén Eigenmode Active Diagnostic system (AEAD) is remotely operated via the AE Local Manager (AELM), a digital controller running at a *1kHz* clock speed through the JET Real Time Signal Server (RTSS), which controls various plasma operating parameters.

The diagnostic technique uses repetitive sweeps of the driving frequency in a pre-defined range, controlled in real-time with the AELM. The plasma response is extracted from background noise using synchronous detection. The AELM is used to identify the resonance corresponding to a plasma global mode. When a resonance is met, the synchronously detected plasma/antenna transfer function describes a circle in the complex plane as the frequency of the exciter is swept across that of the mode. The radius of this circle gives the mode damping rate, which is calculated from a polynomial fit of the complex transfer function. When a resonance is found, the AELM locks to that frequency to track the mode in real-time, with a reduced sweep to cover the 2π phase rotation of the signal. The width of the sweep when a mode is being tracked provides a real time, direct estimate of the damping rates.

3. Alfvén Eigenmodes

For the AE range of frequencies, individual resonances are followed throughout the limiter phase of JET plasma pulses. Due to the strong stabilizing effect of the edge shear [4], when the X-point is formed inside the machine the mode amplitude becomes too small and the resonance width too large for the modes to be detected.

Systematic measurements of the frequency and damping rates of stable AEs are taken in JET plasmas with different magnetic configurations. The dependence of the measured damping rates on the plasma parameters, such as density, temperatures, q-profile, magnetic shear, elongation and triangularity, the isotope concentration, provides information on the damping mechanisms for the stable, antenna-driven, low-n AEs. The experimental observations are compared with numerical calculations from giro-kinetic codes and with direct observations of fast particle driven instabilities [1]. Note that the level of plasma turbulence and background noise in the AE frequency range is very modest, which makes it possible to detect stable AEs at very small amplitudes of the perturbed magnetic field, as low as $|\delta B/B|<10^{-8}$, and with damping rates as high as $\gamma/\omega\approx 15\%$.

Figure 1 shows an example of tracking of a n = 1 stable TAE. Along with the plasma parameters, and the TAE frequency evolution, we present here the comparison of the value of the damping rate measured from the width of the frequency sweep and that computed using a full fit of the antenna-plasma transfer function. The excellent agreement between these results confirms that a signal can be generated from the AE excitation and detection system to provide information about the distance of the driven modes from marginal stability. Proof-of-principle experiments in this direction are being designed at JET, along with a new antenna system for the excitation of higher toroidal mode numbers. Different feedback schemes to control the fast particle stability need to be experimented.

One possibility is to reduce the drive by directly reducing the free energy source for the instability, i.e. the fast particle pressure profile. In the case of modes driven by fast ions created by additional heating, this can be achieved simply by controlling the additional heating power. The fast particle drive can also be limited by enhancing the radial transport of resonant ions with large amplitude AEs, driven by an external antenna or using the ICRH beat-wave method [5]. Alternatively, one can increase the background damping, for example by slightly modifying the plasma edge conditions.

4. Low frequency modes in OS plasmas

In a lower frequency range, $f \leq 50kHz$, we have performed measurements of the damping rates of externally driven, stable n = 1 modes to develop a method to monitor their distance from the marginal stability boundary, as sketched in Figure 2. These modes can be destabilised by the large pressure gradients characteristic of the JET OS plasmas, and can grow to large enough amplitudes to significantly affect the plasma performance and cause disruptions. The small mode frequency in the plasma rest frame is Doppler-shifted by the strong plasma rotation, predominantly driven by Neutral Beam Injection (NBI). For a typical high-performance JET OS plasma the toroidal rotation frequency can reach 40 kHz in the plasma centre and 10 kHz at the foot of the Internal Transport Barrier (ITB). Modes with very small frequency in the plasma rest frame can thus be driven and detected by the AEAD.

Pressure-driven n/m=1/2 and 2/4 modes, localised at the q = 2 surface, are observed to be the most deleterious ones for OS conditions. From correlation measurements of the magnetic, fast electron temperature, soft X-ray and fast neutron signals, the radial position of the modes are determined unambiguously, and observed to correspond to the foot of the ITB. As the structure of these modes is predicted to be global, they can be driven by external antennas before they become unstable.

Damping rates in the range $\gamma/\omega \approx 1\%$, for angular frequencies ω imposed on the antenna, i.e. corresponding to the laboratory frame of reference, are found for modes close to the instability limit. As their unstable (pressure-driven) counterpart, these modes are localised at the q = 2 surface, have small frequency (< 3 kHz) in the plasma rest frame, and are associated to a magnetic island located at the foot of the ITB. Figure 3 shows the plasma parameters for a pulse where real-time tracking of a n=1 stable mode with $f_{MHD} \approx 0.7kHz$ was performed. Figure 4 presents, similarly to the TAE case shown in Figure 1, the mode tracking and the damping rates measured from the width of the frequency sweep and computed using the full fit of the antenna-plasma transfer function. Both measurements indicate that the damping is reduced, hence that these modes are approaching the instability boundary as the discharge evolves toward the high performance phase.

Based on these preliminary results, a number of modifications are being implemented in the AELM and RTSS systems to make use of the damping rates measured in real-time with the AEAD for feedback control on additional heating schemes, such as the ICRF and NBI systems. Exploratory experiments in this area are planned for the forthcoming JET campaign.

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References

[1] A.Fasoli et al., *Phys. Plasmas* **7**, 1816-1824 (2000).
[2] C.Gormezano et al., *Phys. Rev. Lett.* **75,** 645 (1995)
[3] A.Fasoli et al., *Phys. Rev. Lett.* **75,** 645 (1995)
[4] A.Jaun et al., accepted for publication in *Nucl. Fusion* **40** (2000).
[5] A.Fasoli et al., *Nucl. Fusion* **36**, 258 (1996).

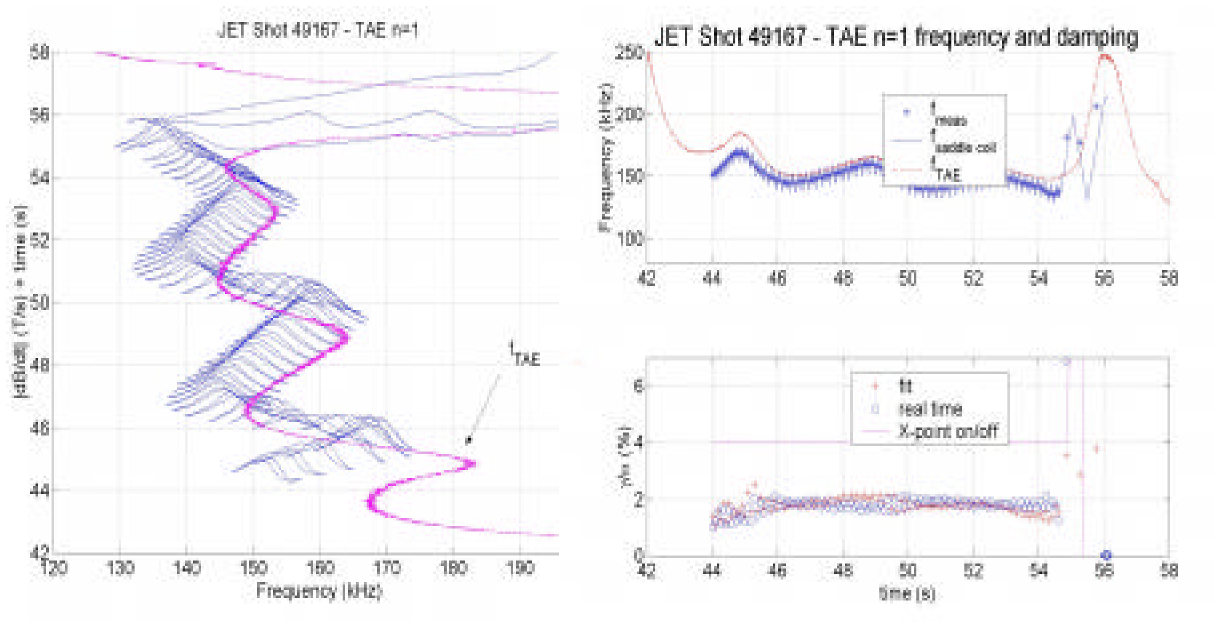

Fig.1 *Tracking of n=1 TAE. Left: frequency. Right: damping rates measured from a fit of the antenna/plasma transfer function and from a real-time estimate of the resonance peak width.*

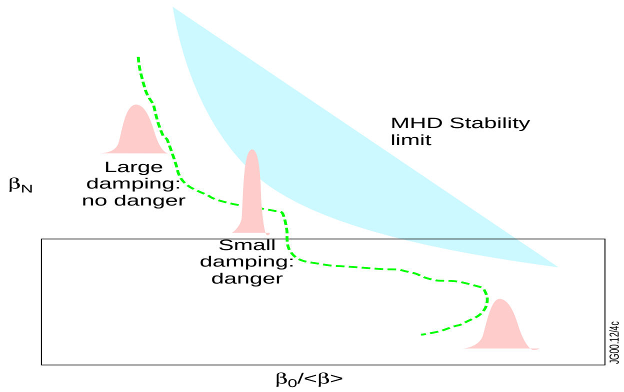

Fig.2 *Use of damping rate measurements to control the mode distance from marginal stability. Here $\beta=2\mu_0 p/B^2$ is the plasma kinetic pressure over magnetic pressure; $\beta_0/<\beta>$ defines the pressure peaking factor as the ratio of the central to volume averaged β-value.*

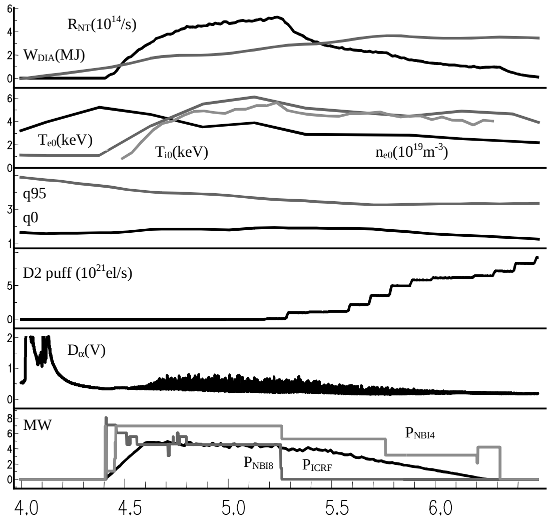

Fig.3 *Parameters for one of the pulses in which stable low frequency n=1 modes are excited.*

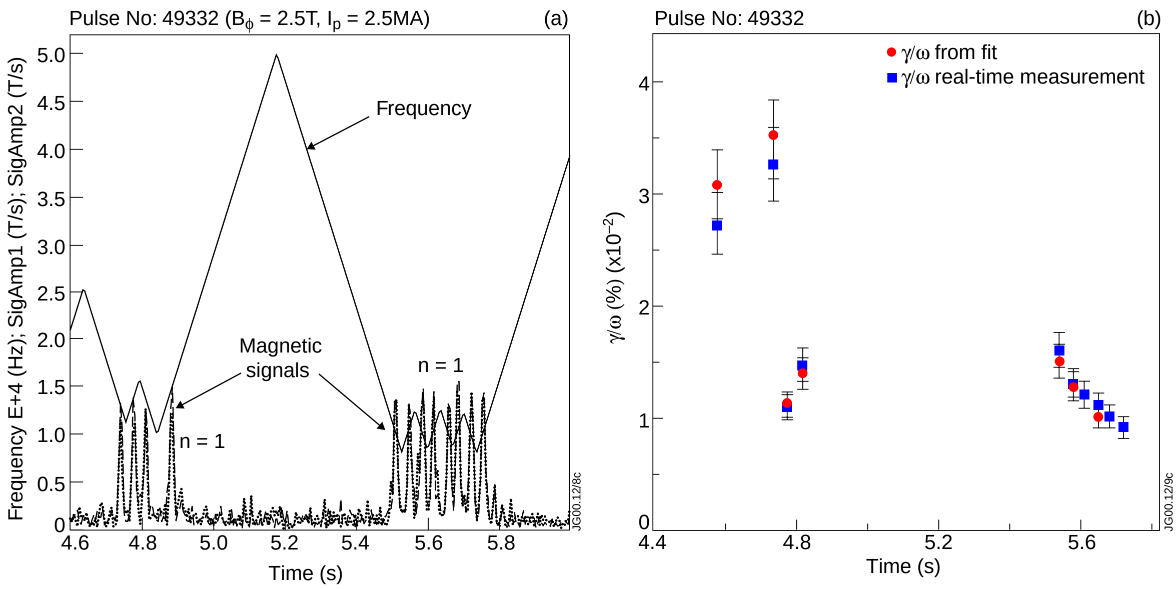

Fig.4 *Real-time frequency tracking (left) and damping rate measurements (right) of the antenna driven n=1 stable mode for a typical JET OS discharge.*