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ABSTRACT

The linear stability properties of global modes that can be driven by resonant energetic particles or by the bulk plasma are studied using an external excitation method based on the JET saddle coil antennas. Low toroidal mode number, stable plasma modes are driven by the saddle coils and detected by magnetic probes to measure their structure, frequency and damping rate, both in the Alfvén Eigenmode (AE) frequency range and in the low frequency Magneto-Hydro-Dynamic (MHD) range. For AEs, the dominant damping mechanisms are identified for different plasma conditions of relevance for reactors. Spectra and damping rates of low frequency MHD modes that are localized at the foot of the internal transport barrier and can affect the plasma performance in advanced tokamak scenarios have been directly measured for the first time. This gives the possibility of monitoring in real time the approach to the instability boundary.

1. INTRODUCTION

The plasma stability to different collective modes is one of the most important physical problems to solve on the way to a magnetic fusion reactor. Magneto-Hydro-Dynamics (MHD) modes that affect the bulk plasma can prevent the achievement and the sustenance of thermonuclear burning conditions, while modes driven resonantly by energetic particles, such as those produced by Ion Cyclotron Resonance Heating (ICRH) or fusion born alpha particles (αs) in DT plasmas, can in turn affect the particle confinement, causing losses and degrading the plasma performance in the approach to ignition.

The JET tokamak has the unique capability of investigating the global mode stability using an external excitation method. Both the high frequency range, 80–400 kHz, typical of Alfvén Eigenmodes (AEs), and the low frequency range, 5–50 kHz, in which internal kinks, tearing and infernal modes lie, are explored [1]. 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 Optimized Shear (OS) regime [2]. After a brief description of the experimental method used for both frequency ranges, experimental results for the two classes of plasma modes are discussed.

2. EXPERIMENTAL METHOD

The JET saddle coils are used as external antennas to drive and detect stable global modes and to evaluate their damping rates. Magnetic perturbations of the order of $|\delta B / B| < 10^{-5}$ are applied to the plasma, low enough to avoid generating significant particle transport or macroscopic perturbations to the plasma equilibrium. The modes are detected synchronously by magnetic probes located at the plasma edge and by internal fluctuation diagnostics such as reflectometer and electron cyclotron emission. Mode structure, frequency and damping rate can be measured directly. The frequency at which the saddle coils are driven is determined in real-time by a digital controller running at 1 kHz and connected to the JET central real time signal server. Repetitive frequency sweeps are applied in a pre-defined range until a resonance corresponding to a plasma global mode is met. The resonance is identified as the transfer function between the antenna and the synchronously detected plasma response from different diagnostic channels describes a circle in the complex plane during one frequency sweep [1]. When a resonance is found, the controller locks to it and tracks the mode with a reduced sweep to maximize the time resolution of the frequency and damping measurements. The damping rate, γ/ω, can be calculated from a fit of the complex transfer function, and corresponds to the radius of the circle in the complex plane. Alternatively, γ/ω can be estimated in real time from the width of the frequency sweep when a mode is being tracked.

3. ALFVÉN EIGENMODE FREQUENCY RANGE

Figure 1 shows an example of tracking of a n = 1 stable Toroidal AE (TAE), in which an individual resonance is followed throughout the limiter phase of a JET discharge. Along with 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 good agreement between these results suggests that a signal can be generated to provide information on the distance of the driven modes from marginal stability. Note that the level of plasma turbulence and background noise in the AE frequency range is very modest, allowing 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 $\gamma/\omega\approx15\%$.

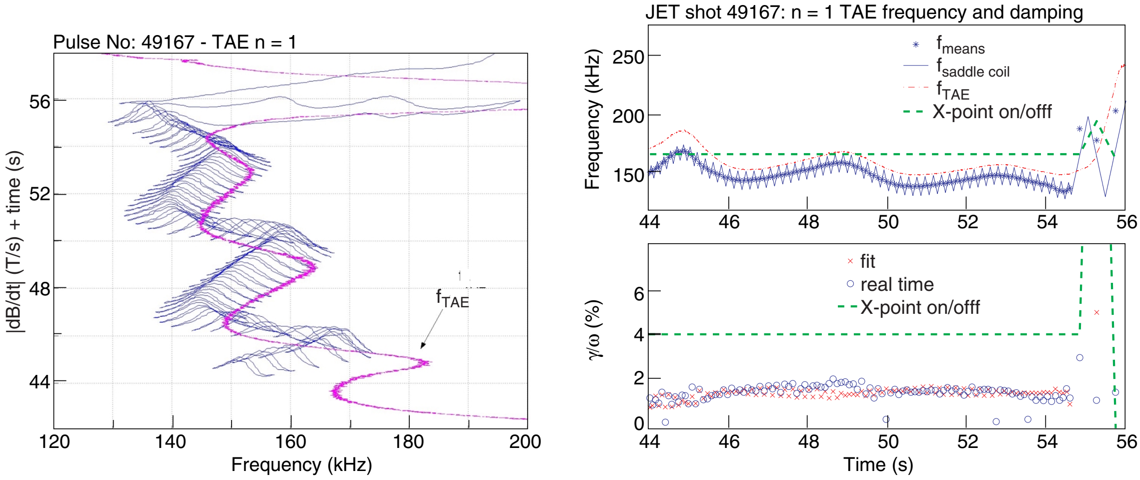

Figure 1: (Left) *Tracking of an n=1 TAE in a JET ohmic, limiter discharge. B_t = 2.5 T; I_p = 2.0 MA; $n_e \sim 2\times10^{19}$ m^{-3}; $T_e \sim T_i \sim$ 3 keV.* (Right) *The frequency of the mode is compared to the expected f_{TAE}, calculated assuming q=1.5; the value of the damping calculated from a fit of the plasma/antenna transfer function is compared to the value obtained from parameters that are accessible in real time. The plasma starts at 40 s.*

Different schemes to control the stability of fast particle driven modes can be considered. One possibility is to reduce the drive by directly reducing the free energy source for the instability, i.e. the fast particle pressure gradient. In the case of modes driven by fast ions created by additional heating, this can be achieved simply by controlling the additional heating power or deposition profile, for example varying the relative power or the frequencies of the different modules of the ICRH antenna. For fusion produced αs, the instability drive can 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 [3]. Alternatively, one can increase the background damping. The study of the AE damping mechanisms, in addition to being very important for the prediction of the stability of future experiments in reactor relevant regimes, can thus lead to possibilities of alpha particle control for burning plasma regimes.

Systematic measurements of the frequency and damping rates of stable modes in the Alfvén Eigenmode frequency range are taken in JET plasmas with different configurations. The dependence of the measured damping rates on plasma parameters such as density, temperatures, q-profile, magnetic shear, elongation and triangularity, and isotope concentration, is analyzed to identify and quantify the different damping mechanisms relevant for reactors. This analysis is performed by comparing the experimental data with the results of numerical codes that calculate the mode stability and with direct observations of fast particle driven instabilities.

By comparing the measured damping rates with the gyro-kinetic code PENN [4], it was found that the damping of the global, low-n AEs driven by the external antennas is primarily due to mode conversion to kinetic Alfvén Waves (kAW), occurring both in the low magnetic shear plasma core and in the high shear edge [5]. Such identification of the damping mechanism was obtained using scans in the plasma elongation and edge shear in typical discharges evolving towards the formation of a magnetic X-point in the plasma [6], and in the plasma isotopic mass for similar discharges [7]. Note that as a result of the strong stabilizing effect of the edge shear, 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. Benchmarking of the gyro-kinetic code to be used to predict AE stability in next step devices was completed [8]. In addition, such comparison made it possible to identify scenarios in which fast-particle driven AEs are stable. For example, it is found that an increasing plasma β has the effect of stabilizing the mode [8,9].

The dependence of the AE damping rates on the plasma shape and magnetic configuration has been systematically investigated in the limiter phase of a number of discharges in which plasmas have similar plasma parameters. The results are shown in Figure 2, where we plot the measured damping rates of externally driven stable $n = 0$ Global AEs (GAEs) and $n = 1$ TAEs as a function of macroscopic plasma shaping parameters, elongation κ and triangularity δ. The extreme sensitivity of the damping rates of low-n, radially extended AEs on the plasma shape and profiles, also observed in the numerical studies, suggests that a scheme to control the stability of such modes in real time could be based on acting on the plasma edge profile.

Stable AEs are also driven in the presence of ICRH and Neutral Beam Injection (NBI)-generated fast particles. The measured effective damping rate can be used in this case to extract information on the fast particle drive [6]. The measured values of γ/ω are used in the prediction of the AE stability limits for given fast particle distributions both for JET and for future ignition experiments. These predictions are directly verified on JET by observing unstable, fast particle driven modes in the presence of different fast particle sources, in the absence of external antenna drive. In addition to determining the marginal stability limits for the AEs, the balance between fast particle drive and background damping regulates the nonlinear development of the instability. Signatures of different nonlinear regimes in AE wave-particle interaction are found in the measured spectra of ICRH-driven modes [10].

The understanding of both the linear and nonlinear stage of the interaction between fast particles and AEs has reached a point whereby significant information about the plasma can be extracted from AE observations. Measurements of AE frequencies provide information about the q-profile, the toroidal rotation and fast plasma density variations in the core. AE stability limits are used to infer variations in the fast particle energy content and radial distribution. From an analysis of the nonlinear evolution of the fast particle driven spectra, the effective collision frequency for the resonant particle and the mode growth rate are estimated.

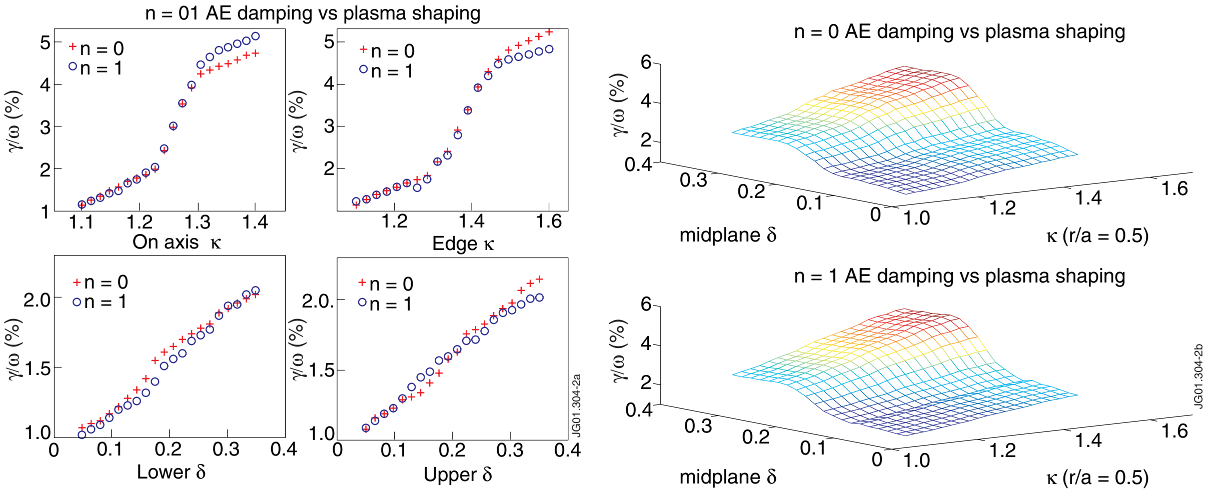

Figure 2: Dependence of the measured damping rate of n = 0 GAEs and n = 1 TAEs on plasma shaping parameters. Note the sharp increase in the damping with the plasma elongation.

4. LOW FREQUENCY MODES IN OPTIMIZED SHEAR PLASMAS

In the low frequency MHD range, measurements of the spectrum and damping rates of externally driven, stable n = 1 modes have been performed to develop a method to monitor their distance from the marginal stability boundary. These modes can be destabilized by the large pressure gradients characteristic of the JET Optimized Shear (OS) plasmas, significantly affect the plasma performance and cause disruptions. The small mode frequency in the plasma rest frame is Doppler-shifted by the strong, predominantly NBI-driven plasma rotation. For a typical high-performance JET OS plasma the toroidal rotation frequency can reach 40 kHz in the plasma center and 10 kHz in the region of the Internal Transport Barrier (ITB). Modes with very small frequency in the plasma rest frame that extend radially to the plasma edge can thus be driven and detected by the saddle coil system. The modes that appear to affect plasma performance are characterized generally by poloidal and toroidal mode numbers m/n = 2/1 and m/n = 4/2, i.e. are localized at the q = 2 surface. From correlation measurements of the magnetic, fast electron temperature, soft X-ray and fast neutron signals, the radial position of the modes are determined, and observed to correspond to the foot of the ITB.

Values of γ/ω of the order of 0.1% are found for the externally driven n = 1 modes, indicating proximity to the instability limit. Later in the same discharge these modes are driven unstable and reach much larger amplitudes, as seen in the magnetic fluctuation spectrogram. An example of these preliminary experiments is given in Figure 3. The γ/ω 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. By measuring the resonance width of the externally driven stable modes, one could monitor in real time the distance from the instability boundary. Feedback control schemes to avoid unstable domains could be designed, based on controlling parameters such as edge conditions or plasma auxiliary heating power.

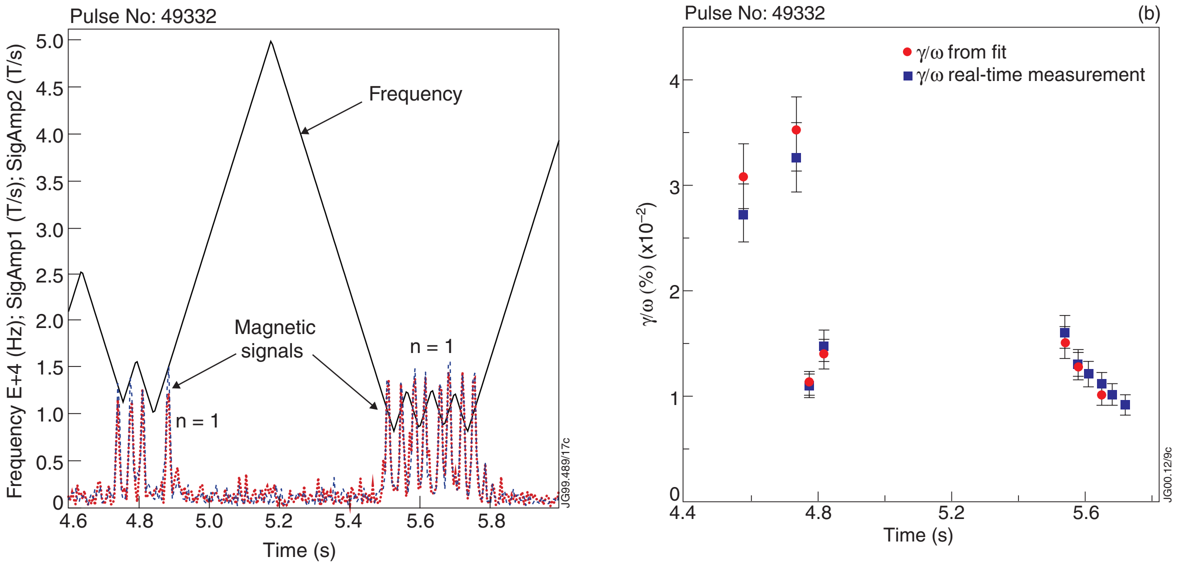

Figure 3: *Frequency tracking (left) and damping rates (right) for antenna driven n = 1 modes in a typical JET Optimized Shear discharge.*

CONCLUSIONS

Systematic studies of the stability of low toroidal mode number MHD modes in the AE frequency range have been performed at JET using an external antenna excitation scheme. Damping mechanisms have been identified and quantified for a variety of reactor relevant regimes. A strong dependence of AE damping rates on plasma shape parameters has been observed, which could be used in combination with real time damping measurements to control the fast particle stability. Extension of the technique to low frequency modes led to the first measurements of the damping rate of stable global MHD mode, of relevance for the JET advanced tokamak scenarios. Further investigations are needed to assess the stability and the possibility of controlling modes with intermediate toroidal mode numbers, expected to be unstable in large devices. A new antenna structure, able to launch these higher mode numbers in the plasma is being designed with this purpose to replace the existing saddle coils.

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