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ABSTRACT

Experiments are conducted on JET to assess the potential for plasma diagnostic spectroscopy and mode stability control of Alfvén Eigenmodes (AEs), excited by external antennas and by energetic particles. Information on the time evolution of the non-monotonic current profile in advanced scenarios can be obtained from the frequency and mode number of AEs driven by energetic particles. By synchronously detecting the antenna-driven perturbations, the damping rate of low-n AEs can be measured in realtime. The dependence of the AE damping rate on the edge plasma shape may lead to the development of feedback control schemes for these modes.

1. INTRODUCTION

The general dispersion relation for shear Alfvén waves, $\omega = k_{\parallel} \upsilon_A$, where $k_{\parallel}$ is the parallel wavevector and $\upsilon_A = B/(4\pi\sum A_i n_i)^{1/2}$ is the Alfvén speed, is modified in a tokamak plasma by the coupling between poloidal harmonics, leading to the appearance of weakly damped Alfvén Eigenmodes (AEs) [1]. These include Toroidal AEs (TAEs), with frequency $f_{TAE} = \upsilon_A / (4\pi qR)$, where q is the value of the safety factor and R the plasma major radius at the mode location. Alfvén waves and AEs provide detailed information on various plasma parameters, which may not be available otherwise, because their dispersion depends upon global and local properties of the system. In plasmas with significant population of energetic ions, such as fusion-born alpha particles, AEs can become unstable due to resonant wave-particle interaction with these ions. If their amplitude exceeds the stochastic threshold for transport, AEs may lead to net fast ion losses, with negative consequences for the plasma confinement and stability.

In this Paper we investigate both of these aspects of the AE physics: the diagnostic use of AEs and their stability, with emphasis on the real-time control possibilities. The use of Alfvén waves and AEs for plasma diagnostic has recently been discussed in Ref.[2], where the active and passive diagnostic techniques used on JET to obtain information on the bulk plasma and fast ion populations using AE spectroscopy have been reviewed. In Ref.[2] we show that measurements of the mode frequency, toroidal mode number and growth rate give accurate information on the plasma isotope ratio, the qprofile, and the radial and velocity gradients of the fast ion distribution. Section 2 of this Paper complements the description presented in Ref.[2] by focusing on the measurement of the poloidal mode numbers for a particular class of AEs, the Alfvén Cascades (ACs) [3], occurring in plasmas with negative magnetic shear in the plasma core, and its possible implications on the inferred current and safety factor profiles. The dependence of the measured damping rate γ / ω upon various background plasma parameters has been investigated extensively at JET [4, 5]. In Section 3 of this Paper, we focus on the real-time measurement of the damping rate of low-n TAEs and show how the dependence of the TAE damping and growth rate γ / ω upon the edge plasma shape in various plasma operating scenarios may lead to possible real-time feedback control for the modes. Section 4 presents the conclusions and an outlook for future experiments.

2. DIAGNOSTIC USE OF AES: MEASUREMENT OF THE POLOIDAL MODE NUMBER FOR THE ALFVÉN CASCADES AND IMPLICATIONS FOR Q(R)

Passive AE spectroscopy consists in observing collective modes driven unstable by fast particles using edge (magnetic probes) and internal (reflectometer, ECE) fluctuation measurements [2]. These are collected and digitized for 4s at 1MHz using an 8-channel data acquisition system [6]. Unstable modes with amplitudes as low as $|\delta B| \approx 10^{-8}$T are routinely detected. The various probes are calibrated in the frequency range $30 \leq f(kHz) \leq 450$, which allows for the correct determination of the mode amplitude and phase. The mode numbers are obtained with a linear fit of the measured phase difference between adjacent pick-up coils as a function of the probe angle in the toroidal (poloidal) direction, $\Delta phase = constant + n(m) \times \Delta angle$. Toroidal mode numbers up to $|n| \leq 30$ can be reliably measured using 3 pick-up coils. To obtain the poloidal mode numbers, the physical position of the magnetic probes, mounted on the vessel, has to be corrected for the curvature of the poloidal magnetic field lines at the mode radial location, the so-called theta-star correction of the probe angle θ^{PROBE}[7]:

$$\theta_*^{PROBE} = \theta^{PROBE} - (\Delta' + \epsilon) \sin(\theta^{PROBE}) + \left(\kappa' - \frac{\kappa}{R}\right)\sin(2 \times \theta^{PROBE}) - \left(\delta' - \frac{2\delta}{R}\right)\sin(3 \times \theta^{PROBE}) + O(\epsilon^4) \qquad (1)$$

Here Δ is the Shafranov shift, $\epsilon = r/R$ is the local inverse aspect ratio, κ and δ are respectively the local elongation and triangularity, and the prime sign indicates the radial derivative with respect to the normalized poloidal flux $\psi_N = \psi(r)/\psi(r=a)$, a being the plasma minor radius. All quantities entering Eq.1 must be evaluated at the mode resonant surface, where q=m/n. Poloidal mode numbers up to $|m| \leq 30$, depending on the precise value of the Shafranov shift, elongation and triangularity at the mode resonant surface, are measured using three or four probes on the low magnetic field side, upper midplane. The small number of poloidal coils available on JET and the need for an accurate, time dependent equilibrium reconstruction can thus sometimes limit the accuracy of the m's [7].

In advanced tokamak scenarios, such as the JET Reversed Shear (RS) experiments [8], characterized by a non monotonic q-profile with electron and ion core transport barriers, it is very important to know the time evolution of the q-profile, since the appearance of an internal transport barrier is often related to a particular rational q-surface entering the plasma. In discharges with a deeply non-monotonic q-profile, produced by lower hybrid current drive applied during the initial ohmic current ramp-up phase, a new class of energetic particle modes [9], known as the Alfvén Cascades (ACs), has been observed [3, 10]. The dispersion relation for the ACs is given by [3, 10]

$$f_{AC}(t) \approx \left| \frac{m}{q_{MIN}(t)} - n \right| \cdot \frac{\upsilon_A(t)}{2\pi R_0} + \delta\tilde{} \left(\beta_{FAST}, \frac{d^2q}{dr^2} \right) \qquad (2)$$

Here R_0 is the position of the magnetic axis, q_{MIN} is the point of minimum q(r), and δf is a small deviation of the cascade frequency from the Alfvén continuum, depending on the second derivative of q(r) at the point of zero magnetic shear and on the fast ion pressure β_{FAST}. ACs appear in the experiment only above a certain frequency, since the non-local continuum damping decreases exponentially with increasing mode frequency [10]. From Eq.2, it is clear that each cascade

approaches the zero-frequency value when $q_{MIN}=m/n$. The Motional Stark Effect (MSE) measurements of the current profile are not usually available on JET during the current ramp-up phase, and therefore the ACs can provide a good indication for the appearance of a particular q-surface in the plasma. If no information on the poloidal mode number for the ACs is available, even a single MSE measurement later during the main heating phase is usually sufficient to obtain the value of q_{MIN} associated with the appearance of a particular cascade earlier in the discharge [2, 3]. Recent measurements of the poloidal mode number for the ACs in experiments with vanishing (and possibly negative) core current, have indicated that some cascades have positive helicity (m>0, n>0), while other have negative helicity (m<0, n>0). Figure 1 shows an example of such measurements. The different helicity is apparent in the calibrated magnetic signals, which show that the phase difference measured between adjacent probes rotates in opposite direction in the poloidal plane for modes with a positive toroidal mode number but opposite helicity. ACs are often difficult to detect with internal measurements, since their amplitude in the core is as low as $|\delta B|$ $\approx 10^{-7}$T, however from crosscorrelation measurements we infer that ACs with positive helicity are located around r/a $\approx 0.4 \div 0.5$, whereas ACs with negative helicity are located around r/a $\approx 0.1 \div 0.2$.

Whereas positive-helicity ACs satisfy the dispersion relation of Eq.2 and their appearance shows an excellent agreement with the MSE measurement of the q-profile towards mid-radius, negative-helicity ACs can only satisfy the dispersion relation of Eq.2 if q is negative in the plasma core. If that is the case, the negative-helicity ACs shown in fig.1, located around r/a ≈ 0.1, are associated with q=-5, giving a total integrated current negative in the plasma core, I_p(r/a ≤ 0.1) $\approx$-10kA, over a time scale comparable with the current diffusion time in such plasmas.

The MSE measurements of the core current density profile show that in such plasmas a region of zero current can exist over a few hundreds of milliseconds. The typical error bar on the MSE measurementis of the order of ±30kA, which makes a negative current of the order of –10kA practically undetectable.Further more, various theoretical models predict that, if it becomes negative, the core current is effectively clamped to zero over a few milliseconds time scale by a n=0 axisymmetric mode [11]. A possible reason for the observation of negative-helicity ACs may be that the standard equilibrium reconstruction required to compute the poloidal mode numbers, and particularly the assumption of nested flux surfaces and the definition of the Shafranov shift, are not adequate in experiments where the toroidal current (hence the poloidal field) is zero over a significant region of the plasma core. In these cases the poloidal mode number is not a good quantum number since |q|=|m/n|$\rightarrow\infty$, which may lead to possible misinterpretation of the measured m's. New equilibrium solvers are being developed to tackle this problem [12], and the issue of how to correctly deduce the poloidal mode number in such experiments is the subject of ongoing analysis.

3. REAL TIME MEASUREMENT OF THE DAMPING RATE OF LOW-N TAES

The four JET saddle coils are used as in-vessel antennas to drive stable AEs with low toroidal and poloidal mode number, |n, m| = 0 $\div$2. Using the antenna excitation, collective modes appear as

resonances in the synchronously measured plasma response, as previously discussed in Refs.[2, 4, 13]. A digital real-time control system, the Alfvén Eigenmodes Local Manager (AELM), running at a 1ms clock rate, is used to perform individual resonance tracking and obtain real-time measurements of the mode frequency and damping rate. The AELM varies the antenna driving frequency linearly around the initial guess for the AE resonance. When a resonance is met, the exciter frequency is swept back and forth around it. The width and the center of the frequency scan, corresponding to the mode frequency and damping rate, are measured and made available to the real-time system. The time taken to cross each resonance, of the order of 10÷50ms, represents the time resolution of the AE measurements. Figure 2 illustrates an example of tracking a n=1 stable TAE in ohmic plasmas in limiter configuration: note that for a stable, antenna-driven, plasma resonance, the mode amplitude is a Lorenzian function of the frequency [4]. Figure 3 shows $(\gamma/\omega)_{REAL-TIME}$, the value obtained in real-time from the width of the frequency sweep, and $(\gamma/\omega)_{FIT}$, the value obtained from the fit of the antenna-plasma transfer function [4], for an ohmic limiter discharge. We notice that $(\gamma/\omega)_{REAL-TIME}$ follows very closely $(\gamma/\omega)_{FIT}$. A similar agreement is obtained in a variety of limiter discharges, including those with low power additional heating, such as Ion Cyclotron Resonance Frequency (ICRF) and Neutral Beam Injection (NBI) heating.

The dependence on the edge magnetic shear and shape of γ/ω for n = 0 Global AEs (GAEs) and n = 1 TAEs has been experimentally investigated in Ref.[14], where it was found that γ/ω increases sharply with the edge elongation and triangularity. Figures 4(a) and 4(b) show the results of recent experiments aimed at measuring the TAE excitation threshold, using the drive provided by resonant NBI ions at $\upsilon_{\|NBI}= \upsilon_A$, as a function of the edge magnetic shear. For similar plasma conditions, one needs $^1/_3$ NBI power ($P_{NBI} = 6$MW compared to $P_{NBI} = 9$MW), and further away from the resonant $\upsilon_\|NBI \approx \upsilon_A$ ($\upsilon_\|NBI \approx 0.8\ \upsilon_A$ compared to $\upsilon_\|NBI \approx 0.95\ \upsilon_A$ due to a different plasma density) to destabilize 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, $P_{NBI}=6$MW is not sufficient to destabilize n=0 ÷2 TAEs for $\upsilon_\|$ NBI $\approx 0.8\ \upsilon_A$. This result confirms earlier predictions and measurements on the importance of the magnetic shear to stabilize TAEs in plasmas with monotonic qprofiles. This effect appears to be weaker for radially localized n = 5 ÷7 TAEs than for global n = 0 ÷2 TAEs, as predicted by the gyrokinetic code PENN [5, 15]. In X-point plasmas with high edge magnetic shear but non-monotonic q-profile and electron (and ion) core transport barrier, such as the JET RS scenarios, $P_{NBI}=5$MW is sufficient to destabilize n=3 ÷5 AEs even at $\upsilon_\|$ NBI $\approx 0.3\ \upsilon_A$, as shown in fig.4c. This could be related to the coupling between kinetic and drift Alfvén waves in plasmas with a deeply non-monotonic q-profile and negative magnetic shear in the plasma core, and an ITER-FEAT scenario with $q_0 = 4.5$ is predicted to be unstable to such modes [16].

In fusion experiments aimed at reaching ignition, it will be important to control the stability of global AEs that may be driven unstable by large populations of resonating fast ions, such as fusion born alpha particles. The strong dependence of the AE damping rate upon the edge shape suggests

a method to control in real-time the stability of fast ions resonating with low-n TAEs, due to the good agreement between $(\gamma/\omega)_{FIT}$ and $(\gamma/\omega)_{REAL-TIME}$. Based on a command generated from $(\gamma/\omega)_{REAL-TIME}$, 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. Dedicated experiments along this line are planned for the forthcoming JET campaigns.

4. SUMMARY AND OUTLINE OF FUTURE WORK

Alfvén eigenmodes have been extensively studied at JET over the last few years with two aims: to obtain detailed information on the background plasma, and to determine the dependence of the AE stability limits upon various plasma parameters to provide accurate predictions for future ignition experiments.

As shown here and in Ref.[2], information on the plasma isotope ratio, q-profile and toroidal rotation frequency can be extracted from the mode frequency. For unstable modes, the growth rate provides insight into the evolution of the fast ion distribution function. For stable modes, the damping rate allows to study the mode stability limit as function of the background plasma parameters, with potential for feedback control.

In plasmas with a monotonic q-profile, the low-n modes driven by the saddle coils are strongly damped as the edge magnetic shear increases, thus becoming undetectable during the X-point phase of the discharge. On the other hand, the AEs most easily destabilized in JET by energetic ions in such plasmas have higher mode number, typically $n = 4 \div 10$, and modes with even higher n's are predicted to be the most dangerous for ITER. In order to be able to actively excite and track the modes that are most naturally destabilized by the fast ion populations, a set of new high-n antennas is being designed for installation on JET during the 2004 shutdown. These antennas will also constitute a test-bed for the use of the active spectroscopy technique in these experiments.

ACKNOWLEDGEMENTS

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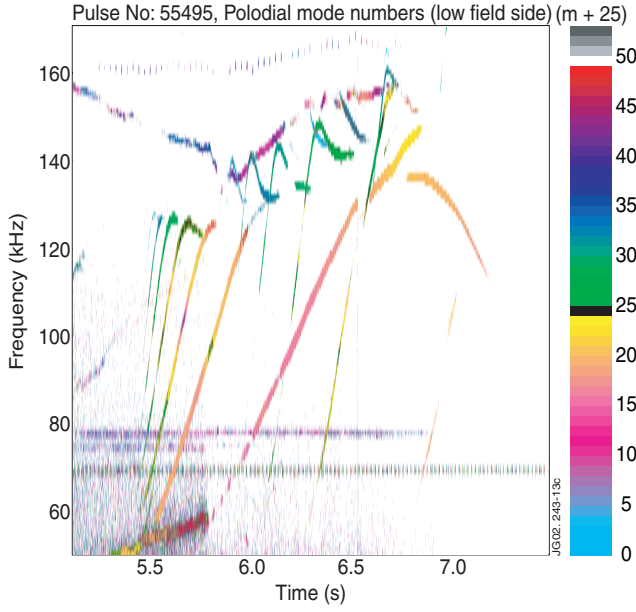[16]. A.Jaun, A.Fasoli, D.Testa, J.Vaclavik, L.Villard, Plasma Phys. Contr. Fusion 43, 207 (2001).

Figure 1: Measurement of the polodial mode number for the ACs in a plasma with a non-monoatonic q-profile. In this discharge ACs with negative helicity can fit the dispersion relation of Eq.2 only if the integrated total current is slightly negative in the plasma core, $I_p(r/a \leq 0.1) \approx -10kA$.
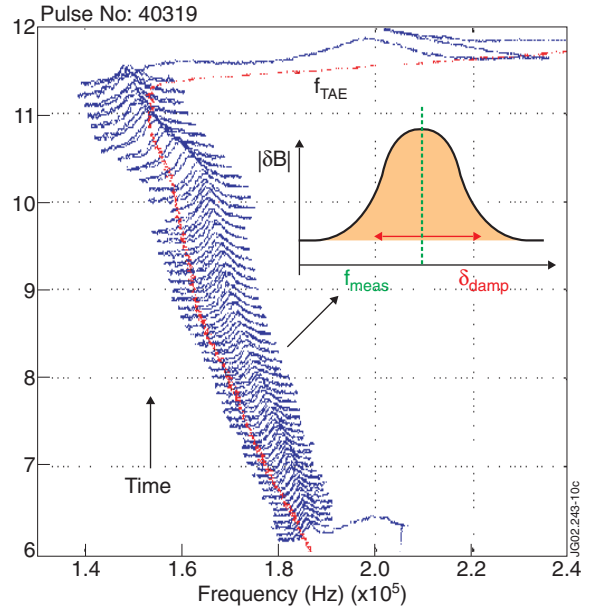

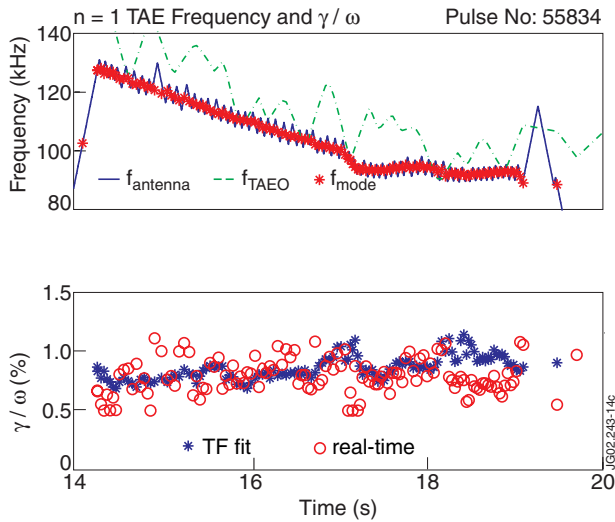*Figure 2: Real-time tracking of a n=1 TAE in an ohmic plasma in limiter configuration.*

Figure 3: The damping rate for a n=1 TAE measured in real time and computed from the full fit of the antenna-plasma transfer function, showing a very good agreement.
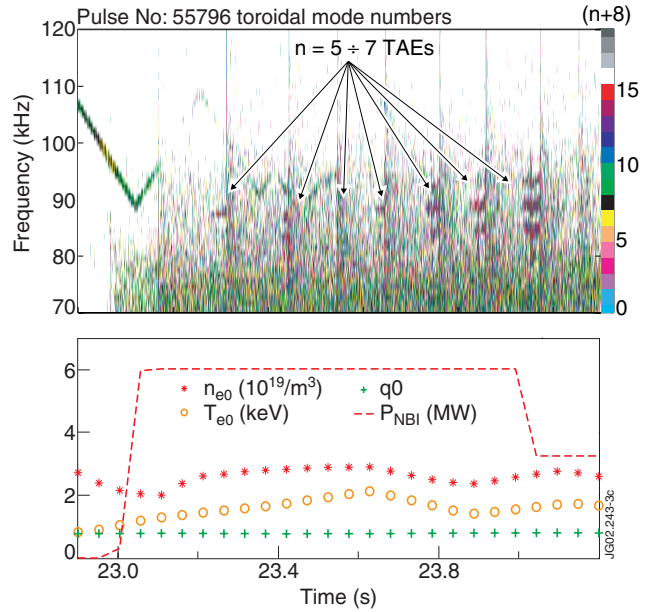

Figure 4(a): Measurement of the TAE excitation threshold, using the NBI ion drive, in a limiter plasma with a monotonic q-profile and low edge magnetic shear: here n=5÷7 TAEs become unstable at P_{NBI}=6MW, with $v_{/NBI/} \approx 0.8 \ v_A$.
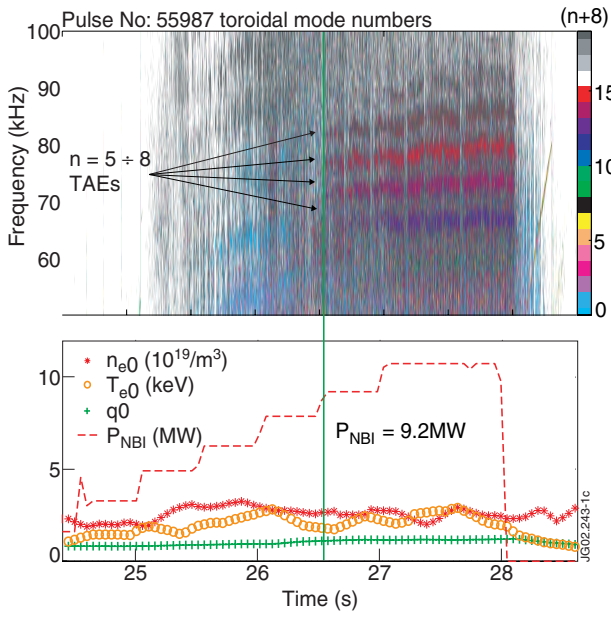
Figure 4(b): Measurement of the TAE excitation threshold, using the NBI ion drive, in a X-point plasma with a monotonic q-profile and high edge magnetic shear: here n=5 ÷8 TAEs become unstable at P_{NBI}=9.2MW, with $v_{//NBI} \approx 0.95\ v_A$.
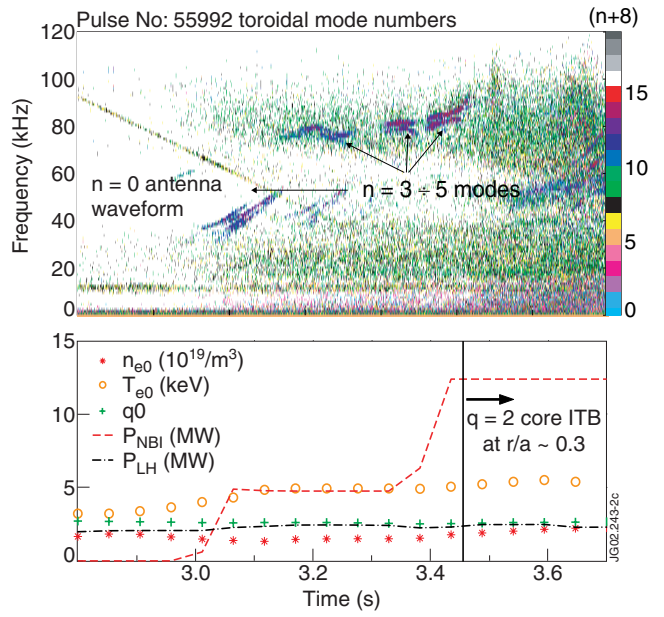
Figure 4(c): Measurement of the TAE excitation threshold, using the NBI ion drive, in a X-point plasma with a non-monotonic q-profile and high edge magnetic shear: here n=3 ÷5 AEs become unstable at P_{NBI}=5MW, with $v_{//NBI} \approx 0.3\ v_A$.