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Measurement of the Damping Rate of High-n Toroidal Alfvén Eigenmodes in JET

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Abstract
A new set of compact in-vessel antennas has been built and installed in JET to provide for the first time the direct measurement of the damping rate (γ/ω) of stable Alfvén Eigenmodes (AEs) with toroidal mode number (n) in the range n=3-15. This paper reports the first quantitative analysis of the measurements of the damping rate for these modes as function of the edge plasma elongation (κ_{95}). We find that the scaling of γ/ω vs. κ_{95} for medium-n Toroidal AEs, with n=3-7, follows the same trend previously measured and explained theoretically for the n=1 and n=2 modes. This confirms the possibility of using the edge shape parameters as a real-time actuator for control of the stability of alpha-particles driven AEs in burning plasma experiments, such as ITER.

1. Introduction
One of the most important physics issues on the way to a fusion reactor is the understanding and control of burning plasmas, the operational regime where the energy carried by the fusion produced alpha particles (αs) exceeds that externally injected to initiate the thermonuclear fusion process. Burning plasmas are characterized by a strong coupling between their various operational elements, such as the pressure profile of the background plasma, which drives the fusion reactivity but may also cause the onset of magneto-hydrodynamic instabilities, and the distribution in phase space of the fusion-born αs and their interaction with the background coherent and turbulent instability spectrum. Present-day fusion experiments approach this problem by investigating separately the individual elements of this regime, by increasing the fusion gain and controlling the background current and pressure driven magnetic instabilities.
One of these elements is the resonant interaction of the αs with coherent plasma waves that can be produced by the αs themselves through an excessive peaking of their pressure profile. This interaction can lead to an efficient energy and momentum exchange between the waves and the αs [1, 2]. If this mechanism leads to a significant spatial re-distribution of the αs themselves up to vessel walls, not only will the overall fusion performance be limited, but also the machine integrity may be affected. Between the various modes that can interact with the αs, Alfvén Eigenmodes (AEs) occupy a special place as they sit in a relatively quiet portion of the plasma electromagnetic fluctuation spectrum, which is well above the frequencies related to drift instabilities driven by a gradient in the background plasma pressure and current, and also well below the ion and electron cyclotron frequency. Hence, AEs represent a direct and clean method of "communication" with the αs, from which not only information on their properties can be obtained, but also on those of the core plasma.
Between all the different classes of AEs [3], of particular interest are AEs with toroidal mode number (n) in the range n~3-15, as these are expected to interact most strongly with the αs [4]. The stability of AEs with these medium-n mode numbers is investigated experimentally in JET using a new set of compact in-vessel antennas, providing a direct measurement of the damping rate (γ/ω) as function of the background plasma parameters for individual modes [5].

[*] Appendix of F.Romanelli, "*Overview of JET Results*", 22nd IAEA Fusion Energy Conference, Geneva, 2008; Nucl. Fus. **49** (2009), 104006.

In this work we present the first quantitative analysis of the data obtained with the new antenna system, focusing on data obtained in ITER-relevant plasma configurations with high edge elongation and magnetic shear. This paper is organised as follows. Section2 presents a brief description of the new JET AE active antenna system. Section3 reports the first quantitative measurements of the damping rate for Toroidal AEs (TAEs) with n=3 and n=7, focussing particularly on the dependence vs. the edge elongation. Finally, in Section4 we present the conclusion of this work and an outline of future activities. A companion paper at this Conference [6] reports on some of the technical aspects of the system and on other measurements of γ/ω, and the Readers are invited to refer to this work for further details.

2. The New Active Antenna System for Excitation of Medium-n Alfvén Eigenmodes

The measurement of the damping rate of AEs has been a long-standing feature of the JET experimental program: the first data were indeed collected for low-n TAEs ($|n|=0\div2$) since the mid-nineties using the saddle coil system [7]. This system had one main limitation, namely the possibility of driving only modes up to $|n|=2$ because of the in-vessel geometry of the saddle coils. After many years of successful operation, during which we obtained in excess of 10^5 individual damping rate measurements, the JET saddle coil system was dismantled during the 2004-2005 shutdown. A new antenna system has been built and installed to replace it and excite magneto-hydrodynamics modes in the Alfvén frequency range ($10\rightarrow500$kHz), keeping similar operational capabilities (max. antenna current and voltage I_{ANT}~15A and V_{ANT}~1kV, max. power output ~5kW) and extending the mode number range to include the medium to high toroidal mode numbers $n=3\div20$ [5].

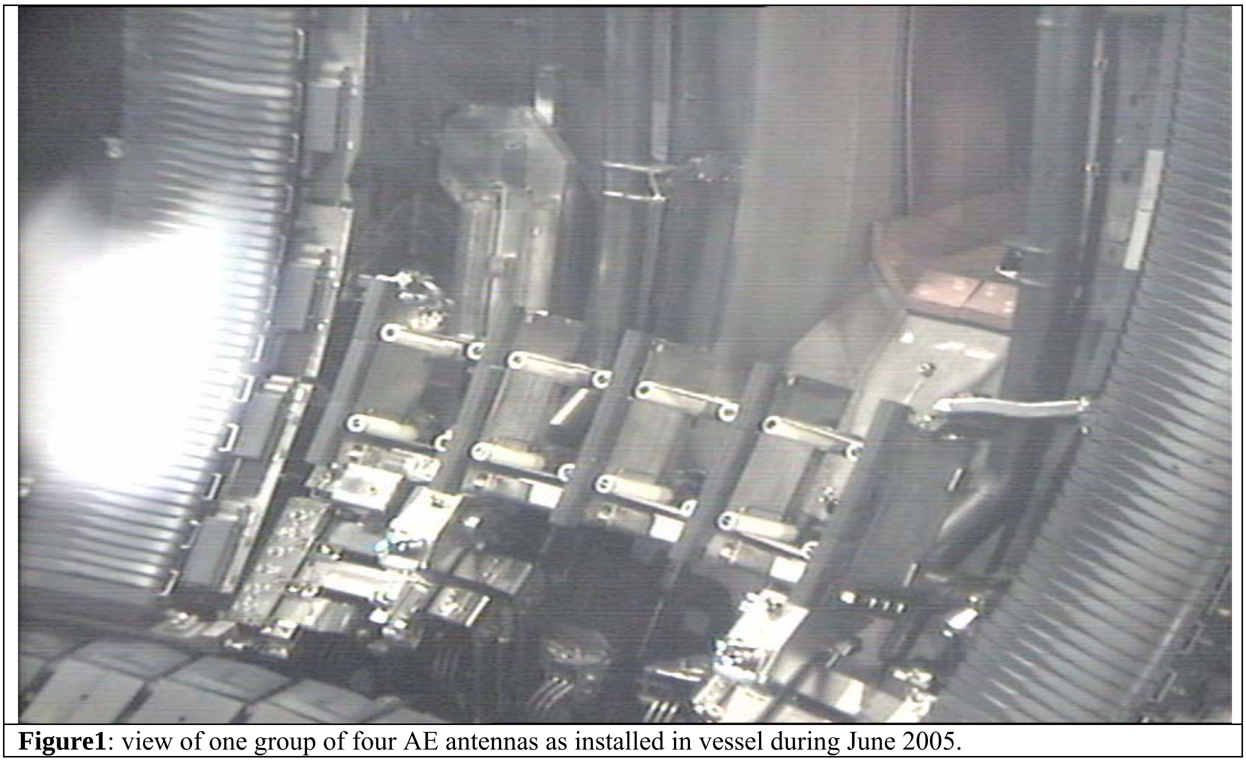

Figure1: view of one group of four AE antennas as installed in vessel during June 2005.

The new antenna system, designed to overcome the n-number limitations of the saddle coils, comprises two assemblies of four toroidally closely-spaced coils each, situated at opposite toroidal locations. Figure1 shows a photo of one of these two assemblies as installed in JET. The maximum antenna current and voltage used for the typical AE excitation experiments are around 10A and 500V, producing a very small antenna-driven magnetic field at the position of the antennas, $|\delta B|$~0.5G per 1A of antenna current, in turn driving a typical $|\delta B|$~0.1G at the plasma edge and $|\delta B|$~0.01G in the plasma core at maximum antenna current. The plasma response to the driven perturbation is measured using synchronous detection. A 1kHz-clock digital control system, the Alfvén Eigenmode Local Manager (AELM), is used to control the AE excitation in real time. The AELM sweeps linearly the antenna frequency around an initial guess for the AE resonance. The AELM is also 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, to obtain the mode frequency and damping rate, as well as the mode amplitude at the different probe locations, with a typical time resolution of the order of 10÷20ms. Any combination of 4 out of the 8 antennas can be chosen with different relative phasing (same/opposite = +/-) to excite different n-spectra, up to n~20, as shown in fig2. Code calculations also demonstrate that this arrangement should provide, for the same JET equilibrium, a coupling to the plasma for an n=5 TAE similar to that achieved with the much bigger saddle coils for an n=2 TAE.

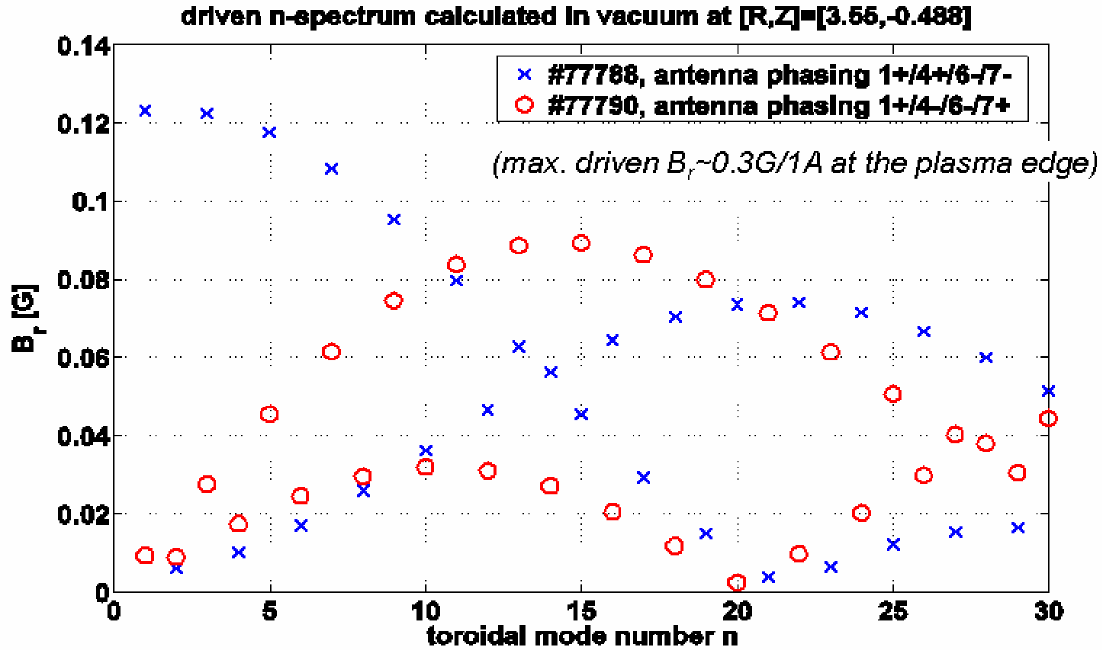

Figure2: two examples of the toroidal spectrum of the radial magnetic field (B_r[G]) driven with the new AE antennas, as calculated in vacuum at the selected position along the plasma major axis [R] and the vertical axis [Z], using the actual antenna current and the antenna-plasma geometry; when operating the system with different antenna phasing, we can drive predominantly n<10 or n~6-15 modes.

The damping rate of |n|≤2 modes in ohmic limiter plasmas was found to be essentially the same as that measured with the saddle coil system [8, 9], hence confirming the robustness of the measurements made with the new antenna system. Despite the much lower magnetic field driven by the antennas on the magnetic axis (at [R,Z]=[3,-0.3]m we have $|\delta B|\sim 1\times 10^{-3}$G for n=5 compared to $|\delta B|\sim 5\times 10^{-2}$G for n=1 and n=2), many harmonics with |n|~0÷12 and low-damping rate $\gamma/\omega<0.2\%$ were found to be simultaneously excited in the plasma. This has prompted the development of a more sophisticated algorithm for mode-number recognition based on the sparse representation of signals [10]. This algorithm has been adapted from its original real-valued data for astronomy applications to deal with complex data in fusion plasmas, and has been successfully validated on JET data [11]. This algorithm has also been deployed in the AELM software, allowing the real-time detection and tracking of individual mode numbers within a CPU-time of <600µs for each 1ms clock cycle. Figure3 shown an example of the real-time detection and tracking of individual n=3, n=5 and n=7 TAEs. This now allows a detailed quantitative analysis of these measurements, as mode numbers can be directly separated in real-time and individually tracked to measure the changes in the mode frequency and γ/ω during the evolution of the plasma background.

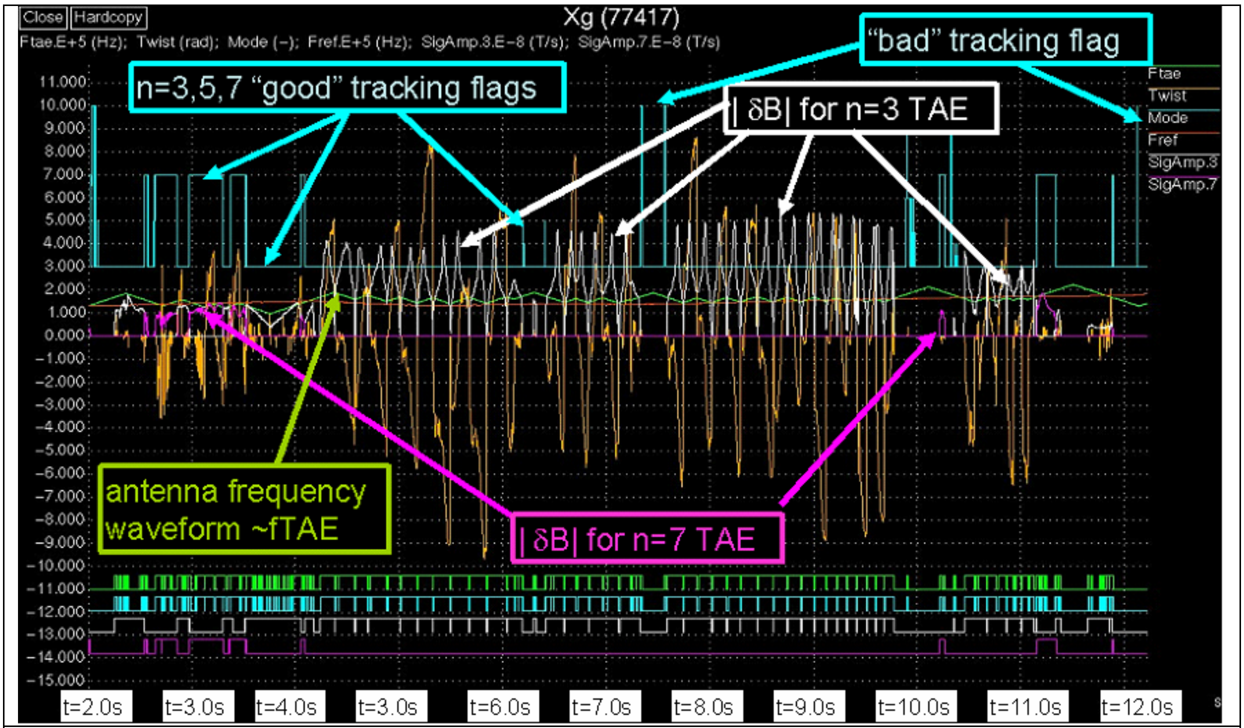

Figure3: an example of real-time tracking of the individual n=3, n=5 and n=7 TAEs; in green the antenna frequency waveform, which follows closely the real-time evolution of the TAE frequency f_{TAE}; the blue flag "mode" is initialised to a "bad" tracking value of n=10, so that when it shows in real time a value different from such flag (in our case being "forced" to look for either n=3 or n=5 or n=7), it indicates that a "good" mode has been detected, so that the AELM locks onto it allowing the evolution of the mode to be tracked in real-time.

3. The Dependence of the Damping Rate of n=3 and n=7 TAEs on the Edge Elongation

As many different damping mechanisms have been theoretically proposed for AEs, systematic experimental studies are needed to obtain the dependence of the AE damping rate on the background plasma parameters. With this approach, one can then find the plasma parameters that are more important for the stability of AEs, and hence determine and quantify with direct comparisons with model calculations the dominant damping mechanisms in current devices. From then on, not only is it relatively simple to extrapolate with confidence to future devices such as ITER when considering the same experimental conditions, but one becomes also able to devise those particular experimental conditions where usually less important damping mechanisms may become dominant, which is in fact what is theoretically foreseen to occur for ITER. As an example of this line of experiments, the ion and electron Landau damping and the radiative damping mechanisms contribute very little in JET to the damping rate of low-n AEs in ohmic plasmas [12, 13], but these are expected to be the dominant damping mechanisms in ITER for AEs with n~5-10 due to the much higher plasma temperature.

In JET, the edge plasma shape and magnetic shear have been found both experimentally [8, 14] and theoretically [15, 16] to be a key ingredient for increasing the damping of both stable, antenna-driven low-n (n=1, n=2) and unstable, fast-ion driven medium-n (n~3-10) AEs. This has motivated previous experimental studies on the Alcator C-mod tokamak where, contrary to the JET results for n=1 and n=2 TAEs, it was found that the damping rate of an n=6 TAE remains essentially invariant when the average lower and upper mid-plane edge elongation δ_{95} is scanned in the range $0.3<\delta_{95}<0.7$, with a similar variation in the edge elongation [17].

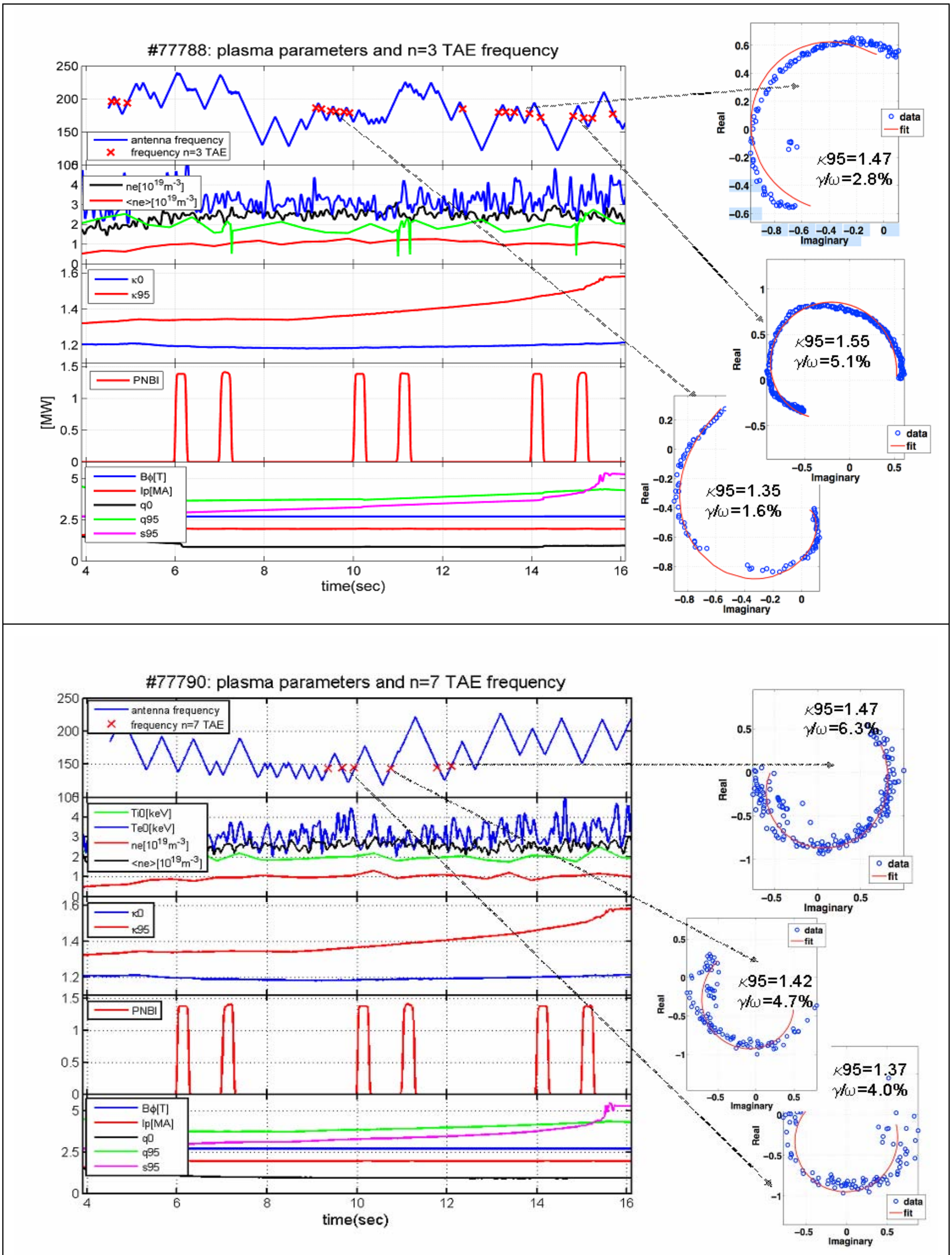

Figure4: overview of the main background plasma parameters for the JET shots #77788 (top frame) and #77790 (bottom frame) where antenna-driven n=3 and n=7 TAE, respectively, were detected and their evolution tracked in real-time; in each case we also show some illustrative examples of the measured δB and its complex-plane fit, which is used to extract γ/ω; here κ is the elongation, T_e and T_i are the electron and ion temperatures, n_e is the plasma density, B_ϕ and I_p are the toroidal magnetic field and plasma current, P_{NBI} is the NBI blip power, q is the safety factor and s the magnetic shear, with the suffixes “0”,“95” and “<>” indicating the core, edge and volume-averaged values, respectively.

With the new set of antennas, it has now become possible in JET to repeat the previous low-n measurements for modes with n~3-10. In this respect, the capability of a real-time detection and tracking of the individual n-components in the antenna driven spectrum constitutes an invaluable tool, which is unique to JET too, to provide accurate testing for code predictions, as it is paramount that the same mode be measured throughout the parameter scan. We show in fig4 the measurement of the damping rate for an n=3 (JET shot #77788, top) and an n=7 (JET shot #77790, bottom) TAE as function of the edge elongation κ_{95} for ohmic plasmas, where the only additional heating was provided by 200ms-long blips of the diagnostic Neutral Beams (NBI), used for the measurement of the ion temperature, rotation and safety factor profiles. These figures show the main plasma parameters and some illustrative examples of the n=3 and n=7 resonances measured in the synchronously detected δB spectrum and their fit in the complex plane. The very good agreement between the measured δB data and the fit reflects the accuracy of the damping rate measurements for each individual mode number.
The different damping rate measurements for the n=3 and n=7 TAEs collected during these two discharges are shown separately in fig5(a,b) as function of κ_{95}. We note an almost linear increase in the damping rate as function of the edge elongation, $\gamma/\omega \propto \kappa_{95}$, for these two modes, which is essentially in very good agreement with the previous JET results for the n=1 and the n=2 TAEs [8], but in clear contradiction with the measurements made for an n=6 TAE in Alcator C-mod [17]. This result is particularly important because it confirms that the same damping mechanism acting upon global, low-n modes, in fact plays a substantial role also for the stability of more core-localised medium-n TAEs, opening up interesting perspectives for real-time control of these modes. For otherwise very similar background plasma parameters, the damping rate for the n=3 TAE increases from γ/ω~0.3% at κ_{95}~1.33 to γ/ω>5% for κ_{95}>1.5, hence a factor 20 increase for a variation in the edge elongation of ~0.17. For the n=7 TAE, this increase in the damping rate is not as sharp, as γ/ω~4% for κ_{95}~1.35 and γ/ω~6.5% for κ_{95}~1.4, i.e. a 60% increase over a variation of ~0.05 in the edge elongation, whereas the corresponding values for the n=3 mode are γ/ω~1.1-1.3% for κ_{95}~1.35 and γ/ω~1.5% for κ_{95}~1.4, i.e. almost no (or a much smaller) variation in the measured damping rate.

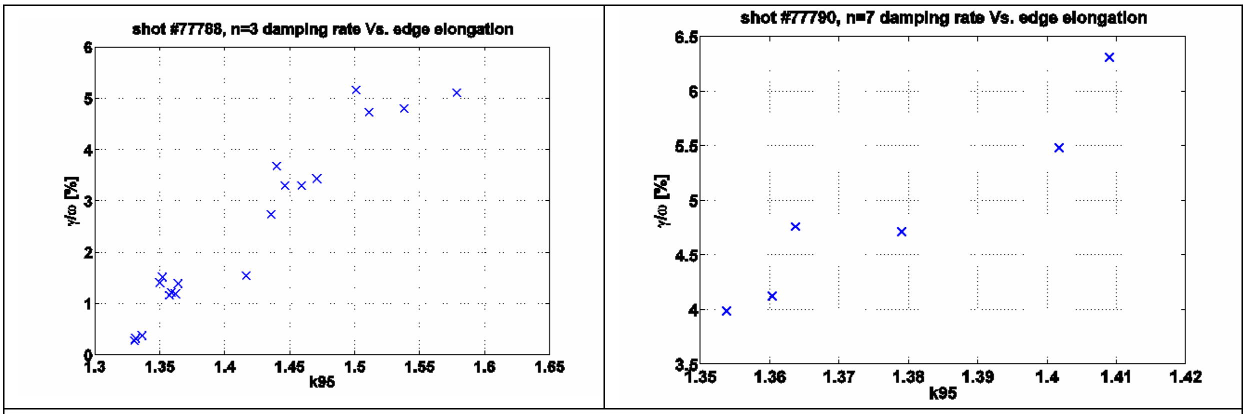

Figure5(a,b): the scaling of the measured damping rate for the n=3 TAE (fig5a, left) and the n=7 TAE (fig5b, right) as function of the edge elongation κ_{95} in two similar JET discharges.

4. Outlook and Future Work

The first measurements of antenna-driven AEs with toroidal mode number in the range n~3-15 have convincingly demonstrated that many of such modes exist at very similar frequencies in the plasma rest frame, such that their frequency separation is less than the modes' half-width at half-maximum, i.e. the damping. This prompted the development of a sophisticated real-time mode number detection and separation algorithm for such a degenerate frequency spectrum, which is based on the sparse representation of signals [10]. Routine measurements of the damping rate for low- and medium- to high-n AEs have now been obtained for various JET operating regimes, with real-time tracking of the driven resonances providing tens of damping rate data for each individual mode number on a single discharge. This result has been obtained using compact antennas with a small effective area, furthermore located rather far away from the plasma edge, at a typical distance in excess of 60mm from the last closed flux surface. This is therefore a very promising technical result in view of a possible use of compact active antennas in ITER for burn control applications.

The first quantitative analysis of the damping rate measurements obtained for medium-n TAEs, n=3 to n=7, has confirmed the experimental scaling of an increase in γ/ω as the edge elongation (hence the edge magnetic shear) is increased. This scaling is in agreement not only with previous measurements in JET for low-n TAEs, but also with theoretical estimates based on the mode conversion of TAEs to kinetic Alfvén Waves at the plasma edge. However, this contradicts results obtained in the Alcator C-mod tokamak, and one possible reason for this discrepancy is the absence of real-time tracking or post-pulse discrimination of the individual mode numbers making up a degenerate spectrum. These first measurements of the damping rate for medium-n TAEs have now been made available for detailed comparisons with theory and models, the results of which are the subject of ongoing work.

On the more technical aspects, an upgrade in the excitation system is planned for the near future, so as to be able to drive independently all the antennas and at higher power. This could create further burning plasma control situations, where the antennas are used to excite modes at higher amplitude to cause a controlled redistribution of the fast particles and prevent an excessive peaking of their pressure gradient. This would then reduce the risk of a more violent fast ion redistribution, which could lead to a total loss of ignition and plasma confinement.

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