

Experiments on Wave-Particle Interaction in the Alfvén Eigenmode Frequency Range at JET

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1. Introduction

Experimental investigations on wave-particle interaction in the Alfvén Eigenmode frequency range are carried out at JET to assess the linear stability properties and the nonlinear development of the modes. Low-n AE damping rates are measured for different ion masses to identify the dominant damping mechanism. The nonlinear interaction of AEs with ICRH-generated fast ions is investigated at a fundamental level by comparing the data with a theoretical model. The technique of external excitation and mode tracking is extended to low frequency MHD instabilities to measure in real-time the proximity to the mode stability limit.

2. AE linear stability: damping and fast particle drive

Low-n stable AEs are driven by the external JET saddle coil antennas and detected synchronously by magnetic probes to measure the mode structure, frequency and damping rate [1]. Individual resonances are followed through the limiter phase of JET discharges. Damping measurements are taken in plasmas with different ion masses to identify the dominant damping mechanism. A comparison with the gyro-kinetic code PENN [2] indicates that AE damping is due to mode conversion to kinetic Alfvén waves, occurring in the low magnetic shear plasma core and in the high shear edge, formed as the X-point is created. Stable AEs are also driven in the presence of ICRH and NBI-generated fast particles. The measured total damping rate contains in this case information on the fast particle drive. In the chosen examples the energy of the NBI ions, 80 keV, corresponds to a sub-Alfvénic ion velocity, $v_{\parallel} < v_A/3$. The beams provide mainly a source of damping both by heating the bulk ions, increasing the ion Landau damping, and by raising the plasma β , effectively strengthening the AE interaction with the Alfvén continuum. The latter is the same mechanism stabilizing against AEs the JET hot ion H-modes, including the high fusion power

D-T discharges [3]. ICRH heated ions, however, reach velocities of the order of v_A and produce a drive for AEs. In Fig. 1 we report the measured total damping rates for an externally driven $n=1$ TAE, for two similar discharges with the same ICRH power ($P_{\text{ICRH}} \sim 3$ MW in H-minority, on axis heating) but different NBI power levels. The discharge on the left has $P_{\text{NBI}} \leq 1.5$ MW, not significantly affecting the plasma parameters. A reduction in the total damping is measured during the ICRH pulse, indicating a drive effect from the ICRH heated ions. In the discharge shown on the right $P_{\text{NBI}} \sim 10$ MW. The data shows that the NBI enhanced damping dominates over the drive created by the ICRH. In both discharges the damping rate reaches the value of $\gamma/\omega \sim 1-2\%$ once the fast particles are thermalized.

3. Nonlinear AE wave-particle interaction

Alfvén Eigenmodes are suitable to explore fundamental nonlinear wave-particle physics as the fast particle population primarily affects the instability growth rate but not the mode structure or frequency. The nonlinear saturation and splitting observed in the spectra of TAEs driven by ICRH-generated fast particles are interpreted using a universal model for near-threshold kinetic instabilities [4]. The observed mode splitting is due to the combination of resonant wave-particle interaction and collision-like relaxation of the resonant particles. The comparison with non-linear theory allows a determination of the instability growth rate and the effective collision frequency in the region of the wave-particle resonance [5]. An example is reported in Fig. 2, where snapshots of the frequency spectrum and the time evolution of the mode amplitude are shown for a single- n TAE. Larger values of the ratio of the mode growth rate to the effective particle collision frequency are expected to give rise to an explosive nonlinear regime, with strong modifications of the particle orbits, redistribution and losses.

4. Real-time determination of distance from marginal stability of plasma modes

The AE active system can also be used to excite and track MHD waves with low toroidal mode number and extending radially to the plasma edge. By monitoring the width, i.e. the damping, of the driven mode, one can evaluate the distance from the marginal stability limit. As the toroidal plasma rotation frequency can reach 20 kHz, modes with small frequency in the plasma frame can be driven by the saddle coil system. These modes can significantly affect the plasma performance in 'optimised shear' regimes [6]. An example of these exploratory experiments is given in Fig. 3. Here the saddle coils drive low amplitude ($\delta B/B < 10^{-5}$) $n=1, 3$ and 5 modes. Very small damping rates ($\gamma/\omega \ll 1\%$) are measured just

before these modes are destabilised and driven to much larger amplitudes by the pressure or current density gradient, as seen in the magnetic fluctuation spectrogram.

5. Conclusions

The AE stability properties are studied at JET over a range of plasma scenarios. Agreement with the predictions of numerical codes leads to reliable extrapolation of the AE stability for ignition experiments. The observed nonlinear evolution of AEs is quantitatively described by a theoretical model. Measurements of the linear and nonlinear AE features provide information on the bulk plasma and the fast particle population. Preliminary experiments using the AE antennas to drive low frequency MHD instabilities suggest the possibility of monitoring in real time the proximity to the marginal stability limit for the driven mode.

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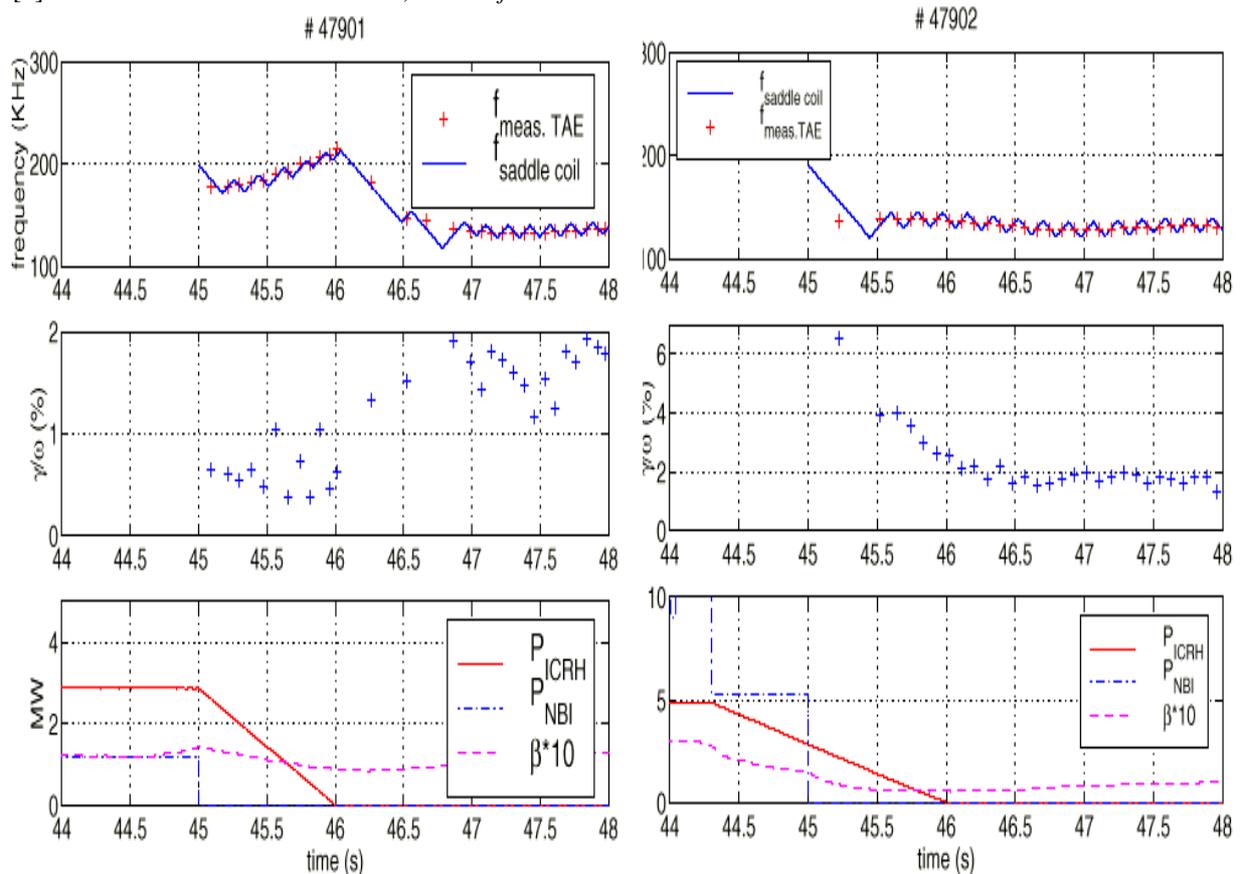


Fig. 1 $n=1$ TAE in limiter plasma: measured γ/ω with and without significant NBI power.

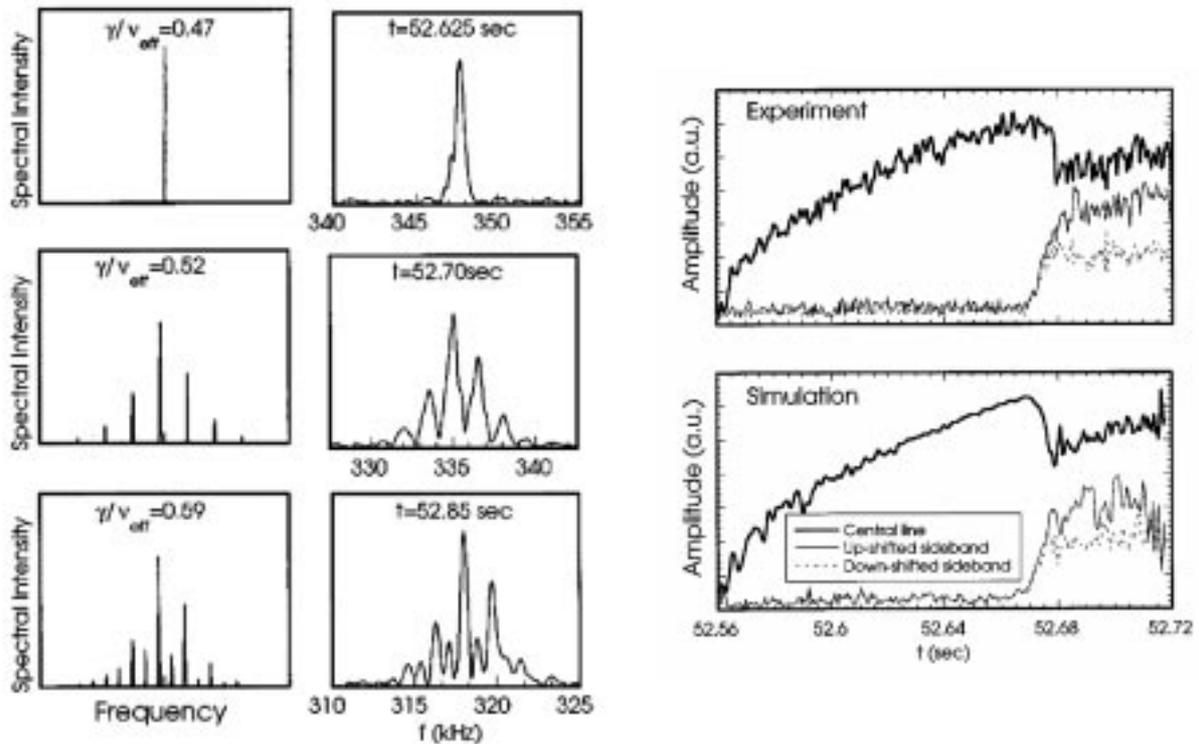


Fig. 2 Left: splitting of the TAE line and period doubling bifurcation in snapshots of the mode power spectrum; the spectrum is calculated for increasing values of γ/v_{eff} (ICRH-driven $n=7$ TAE, Shot 40328). Right: time evolution of the $n=8$ mode (Shot 40328). Top: experimental data. Bottom: simulation results with $\gamma=1.25 \times 10^4$ ($t[\text{s}]-52.56$) $2\pi \text{ s}^{-1}$, $v_{\text{eff}}=2.8 \times 10^3 2\pi \text{ s}^{-1}$.

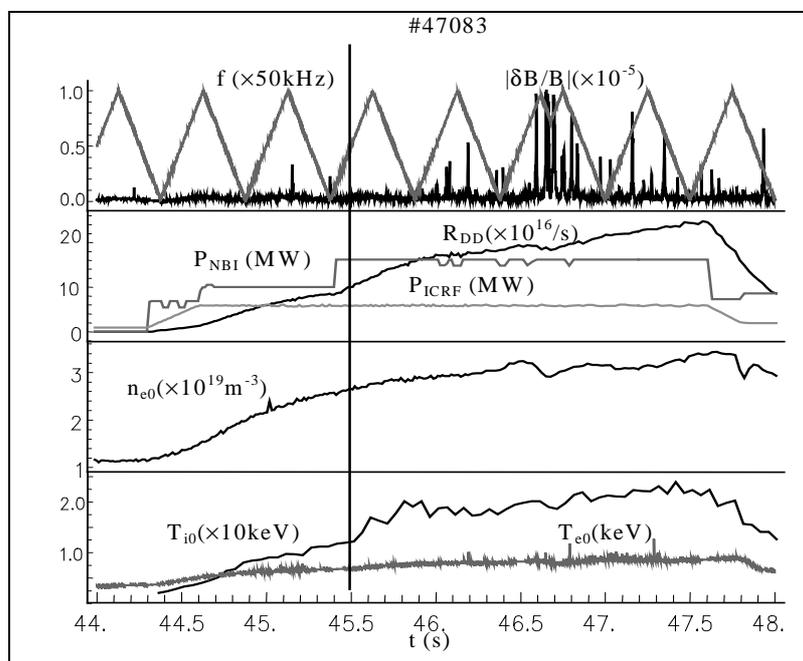


Fig.3 Low frequency, low- n global MHD modes detected synchronously with the JET saddle coil antennas in optimised shear plasma. The modes before $t = 45.5\text{s}$ are purely driven by the saddle coils as they do not appear on magnetic fluctuation spectra. After $t = 45.5\text{s}$ (indicated by the vertical line) the modes become unstable and eventually limit plasma performance.