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Measurement of Alfvén Waves on the JET Tokamak

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ABSTRACT

One of the main purposes of the Alfvén Eigenmodes (AEs) [1] studies on JET is to validate the existing theoretical models and identify the dominant damping mechanisms for global AEs, with the aim to obtain accurate predictions for future burning plasma experiments. As an example of this work, the dependence of the measured damping rate upon the normalized Larmor radius has been analyzed in the conventional tokamak scenario, with a monotonic q-profile, to test the predictions of the NOVA-K code [2]. The AE stability properties have been studied in the presence of the fast ion drive provided by resonant Neutral Beam Injected (NBI) ions with velocities $|\upsilon\|_{NBI}| \approx \upsilon_A$. We have investigated the role of the high central safety factor, $q_0 \geq 2$, on the AE stability in the advanced tokamak regimes, such as the JET Reversed Shear (RS) experiments with non-monotonic q-profile and internal transport barriers, where the ion diamagnetic drift frequency approaches the AE frequency, $\omega_{*i} / \omega_{TAE} \approx 2nq^2\rho_*^2 (R\omega_{pi} / c)$ and $\omega_{*i} / \omega_{AE} > 0.1$.

1. ACTIVE DIAGNOSTIC TECHNIQUE.

The JET saddle coils are used as external antennas to drive and detect stable AEs. The diagnostic technique [3,4,5] uses repetitive sweeps of the driving frequency in a pre-defined range, controlled in real-time. The plasma response is extracted from background noise using synchronous detection, and it is used to identify in real-time the resonance corresponding to a global mode. When a resonance is found, the controller locks to that frequency and tracks the mode, providing a real-time measurement of the mode frequency and damping rate γ / ω.

2. TEST OF THE RADIATIVE DAMPING MODEL.

The *radiative damping model*, as implemented in the NOVA-K code [2], predicts a strong dependence for the damping rate of n = 1 Toroidal AEs (TAEs) upon the kinetic parameter $\lambda = 4(2/5)^{3/2}(m\sigma\rho_{*i} / r) (R / r) 3 / 2 (3 / 4 + T_e / T_i)^{1/2}$: $\gamma / \omega_{RAD} \propto \exp(-\sigma^2 / \lambda)$, where $s = (r / q)\, dq / dr$ is the magnetic shear. NOVA-K also includes trapped electron Landau damping, γ / ω_{ELE}, but does not include continuum damping [6]. Figure 1 shows an example of the test of the radiative damping model, as implemented in NOVA-K, for plasmas with a monotonic q-profile and low edge magnetic shear (limiter configuration). The mode frequency predicted by NOVA-K agrees well with the measurement, but the predicted damping rate $\gamma / \omega_{RAD} + \gamma / \omega_{ELE}$ is a factor 20 smaller than the measured one. A possible reason for this discrepancy is a finite continuum damping near the edge due to the global structure of the n = 1 TAE. This suggests that $\gamma / \omega_{RAD} + \gamma / \omega_{ELE}$ alone may not be sufficient to predict the low-n TAE stability in JET plasmas with monotonic q-profile and low edge magnetic shear. This could also have possible implications for predicting the TAE stability of future burning plasma experiments such as ITER.

3. MEASUREMENT OF THE STABILITY LIMITS AS FUNCTION OF THE EDGE MAGNETIC SHEAR.

A large edge magnetic shear has a strong stabilizing contribution for low-n AEs [7,8]. Using resonant NBI ions with $|\upsilon_{||}| \approx \upsilon_A$, we have measured the excitation threshold for TAEs with different n's in plasma configurations with monotonic q-profile and low (limiter) and high (X-point) edge magnetic shear. In particular, TAEs destabilized by NBI-ions have higher toroidal mode number $n = 3\div10$ [9], than those of the antenna driven (stable) TAEs, which have $n = 0\div2$. The effect of the NBI ion drive on the $n = 1$ TAE damping rate is shown in fig.2 for a limiter plasma where $|\upsilon_{||}| \approx 0.85\ \upsilon_A$: there is no significant variation in γ / ω. This poses a constraint on the velocity spread of the NBI ion distribution function. Figures 3(a) and 3(b) show the results on the excitation threshold for TAEs with different n's in limiter and X-point configurations, respectively. For similar plasma conditions, _ less NBI power (and further away from the resonant $|\upsilon_{||}| / \upsilon_A = 1$ due to a different plasma density) is needed to destabilize TAEs with intermediate n's in plasmas with low edge magnetic shear than with high edge magnetic shear. Conversely, for plasmas with similar low edge magnetic shear and $|\upsilon_{||}| \approx 0.8\ \upsilon_A$, $P_{NBI} = 6$MW is not sufficient to destabilize $n = 0\div2$ TAEs. This result confirms earlier predictions and measurements on the importance of the magnetic shear to stabilize TAEs, but this effect appears to be weaker for $n = 5\div7$ TAEs than for $n = 0\div2$ TAEs [7].

4. ALFVÉN MODE STABILITY IN THE ADVANCED TOKAMAK SCENARIO.

In the advanced tokamak scenario with deeply reversed shear, coupling between kinetic and drift Alfvén waves is expected for $\omega_{*i} / \omega_{TAE} \approx 2nq^2\rho_*^2 (R\omega_{pi} / c) > 0.01n$, and an ITER-FEAT scenario with $q_0 = 4.5$ is predicted to be unstable to such modes [10]. Figures 4a and 4b show the measurements for two JET RS discharges in X-point configuration with a non-monotonic q-profile and electron (and ion) core transport barrier. Here no MeV energy ions were present, which are needed to destabilize TAEs in similar plasmas with a monotonic q-profile. The $n = 0$ modes observed in the experiment do not follow the f_{TAE} (t) frequency scaling and are weakly damped even in the presence of a large edge magnetic shear, during the X-point phase. This could be related to a flat q-profile, with very small (or even negative) magnetic shear in the plasma core, since these weakly damped modes do not appear in similar plasmas with positive magnetic shear, as shown in fig.5. It should be noted that the $n = 0$ modes cannot be driven unstable by fast particles, but can serve as a useful benchmark of theory. Future work in RS plasmas will focus on the reactor relevant and potentially unstable $n > 0$ modes. Intermediate and high-n AEs ($n > 3$) are more easily destabilized on JET, and future burning plasma experiments are predicted to have unstable AEs with even higher n's because of a smaller ρ_{*i}. To study the stability properties of these high-n AEs, new antennas are being designed for future installation in JET.

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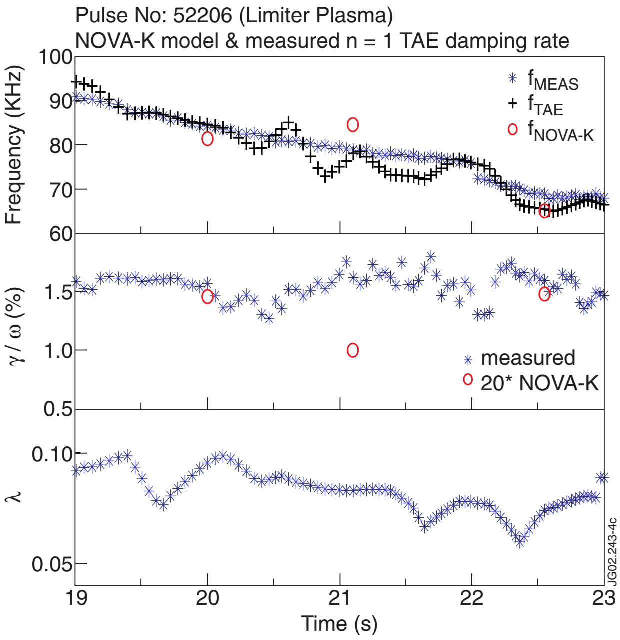

Figure 1: Test of the radiative damping model as implemented in the NOVA-K code.

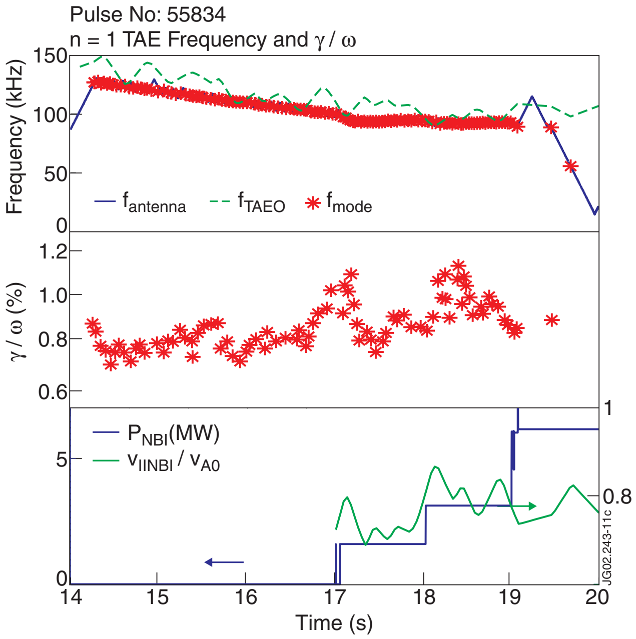

Figure 2: Measurement of the NBI ion drive and n=1 TAE stability limits.

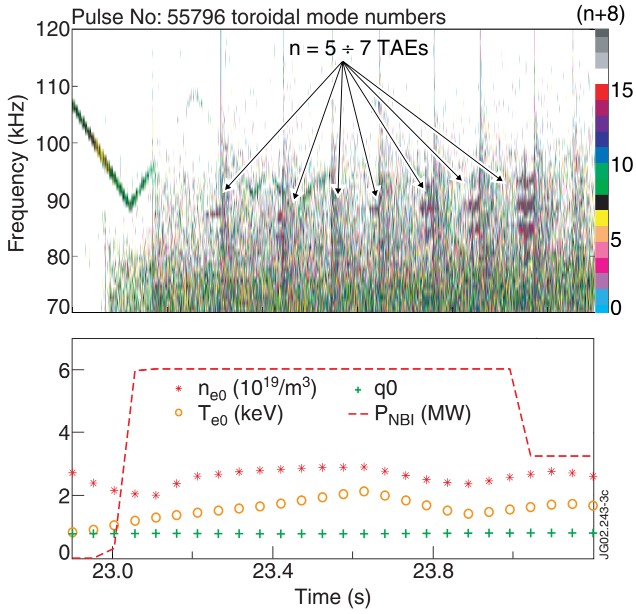

Figure 3(a): Limiter plasma: n = 5÷7 TAEs unstable at P_{NBI} = 6MW, $|u_{||}| \approx 0.8u_A$.

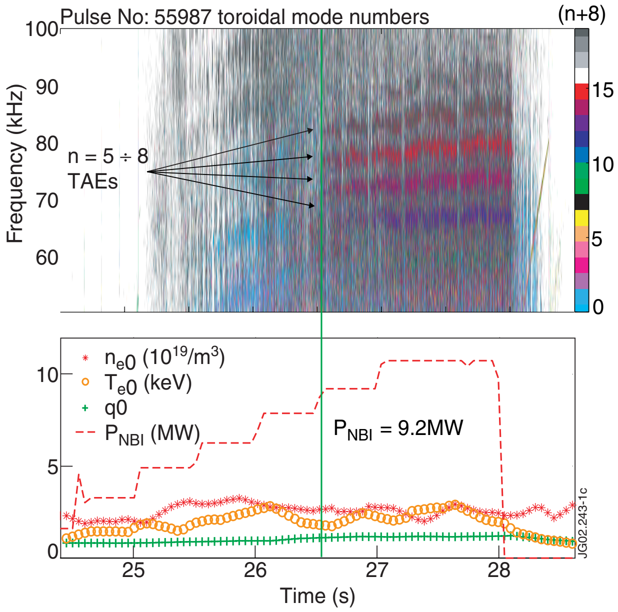

Figure 3(b): X-point plasma: n = 5÷8 TAEs unstable at P_{NBI} = 9.2MW, $|u_{||}| \approx 0.95\ u_A$.

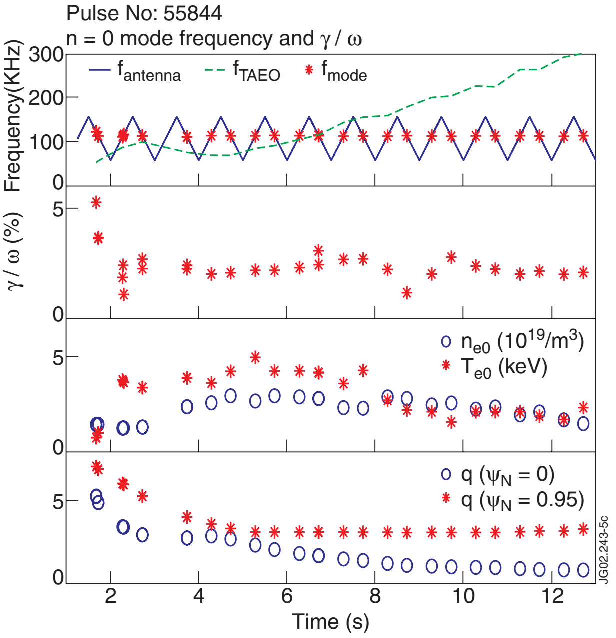

Figure 4(a): Weakly damped n = 0 modes

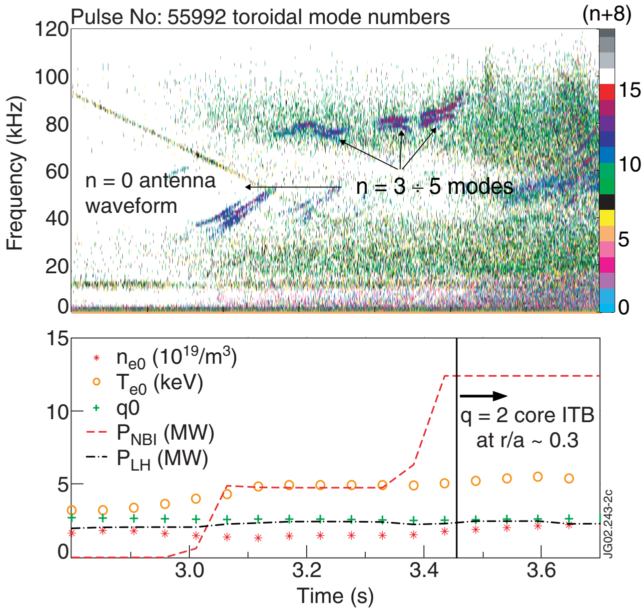

Figure 4(b): Unstable n = 3÷5 modes.

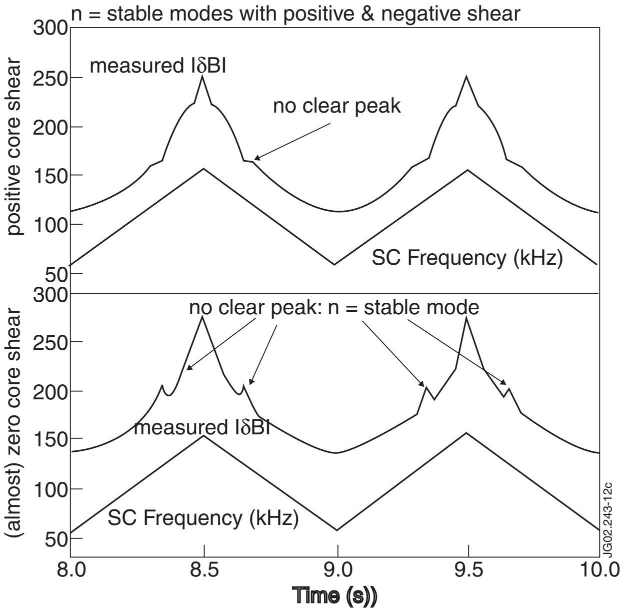

Figure 5. Amplitude of stable n=0 modes for two discharges with monotonic q-profile and positive core magnetic shear (top) and non-monotonic q-profile with almost zero core magnetic shear (bottom).