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

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After many years of successful operation, the JET saddle coil system was dismantled during the 2004-2005 shutdown. A new antenna system was installed to replace it and excite MHD modes in the Alfvén frequency range [1]. Due to their geometry, the saddle coils could drive only low toroidal mode numbers, |n|=0-2. Conversely, the Alfvén Eigenmodes (AEs) that can be driven unstable in JET (and ITER: [2]) by fusion generated alphas or other fast particles have toroidal mode numbers in the range n~5-20. This, and because most of the previous JET measurements were obtained in plasmas with low edge magnetic shear, makes it difficult to extrapolate the low-n results to ITER. These reasons prompted the design of a new system of compact antennas for excitation and measurements of high-n modes.

In this paper we review the antenna design principles and present the first measurements of the frequency and damping rate for n~1-20 TAEs obtained with this new antenna system. These data have been obtained not only in limited plasmas, but also in ITER-relevant X-point plasma configurations with high edge magnetic shear and moderate heating power.

Antenna Design Principles

The new antenna system has been designed to overcome the technical limitations of the old saddle coils. Eight compact (NA~1m^2 compared to NA~15m^2 for one saddle coil) antennas asymmetrically located in the toroidal direction have been built in order to excite a spectrum of high-n AEs using different phasing combinations via a single high current power supply. The antenna design was optimized to achieve for n=5 TAEs a coupling to the plasma similar to that obtained for n=1 TAEs with the saddle coils. Each antenna has a small solenoid-like shape with 18 turns, giving a static self-inductance for each antenna of the order of 80μH. The new AE antennas are divided in two groups of four antennas each, positioned as close as possible to the plasma, with a distance between the first turn of the antenna and the last closed flux surface of the order of 60mm (compared to ~20mm for the saddle coils). Figure 1 shows one assembly of four antennas, which was installed in JET in June 2005. The second group of four antennas is to be installed in October 2007 at the end of the current shutdown.

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*See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), IAEA.

The full technical commissioning (including plasma operation) started in November 2005. The new antenna system has been in routine operation since January 2007 until the end of the recent experimental campaigns. Damping rate measurements were collected for about 1200 discharges, covering essentially all the different JET operating regimes.

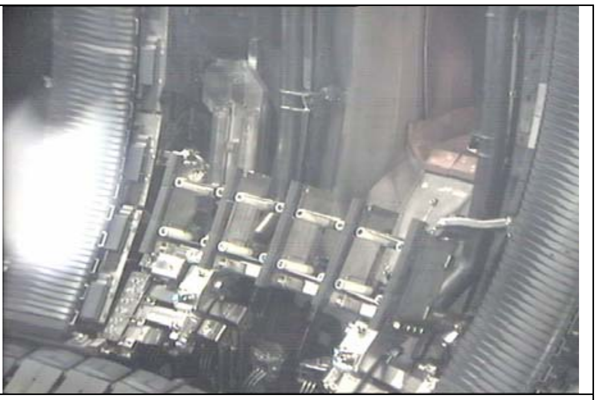


Figure 1. View of one group of four AE antennas as installed in vessel during June 2005.

Figure 2 shows the spectra obtained for two different antenna phasing configurations, driving both low-n and high-n modes. The n-spectrum that can be excited in the plasma by the new antennas extends easily up to n~30 also in an X-point configuration. Real-time mode tracking has been routinely obtained for all antenna excitation configurations for a variety of plasma regimes (in limiter and X-point edge shape), up to moderate heating power (P_{NBI}<6MW). At higher P_{NBI}, background broadband turbulence dominates the synchronously detected signal.

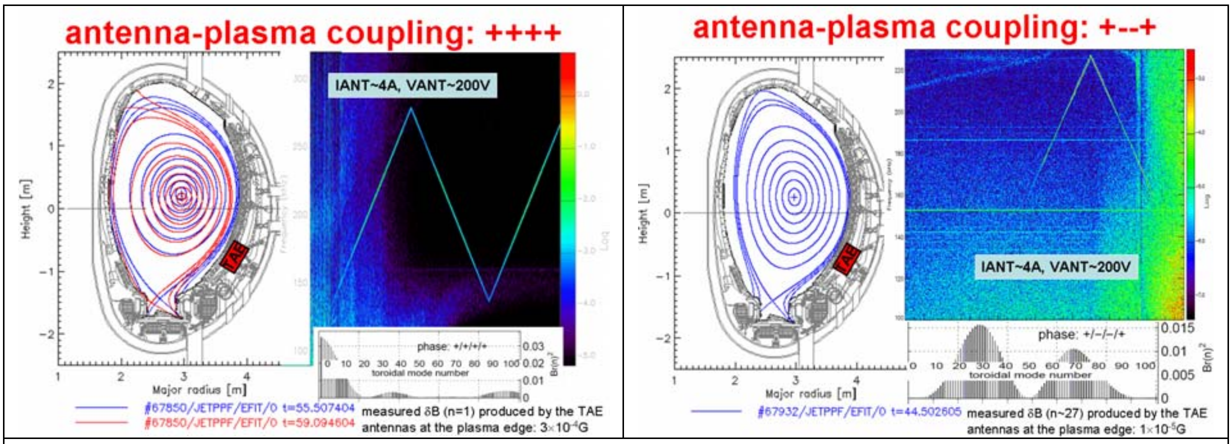


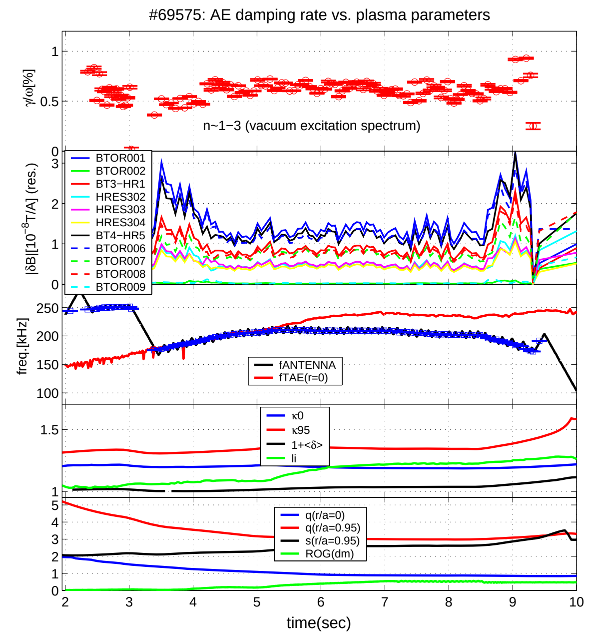
Figure 2. Nominal vacuum and plasma excitation spectra using different antenna phasing configurations.

Problematic Determination of Toroidal Mode Numbers

As shown in fig.2, the spectrum driven in the plasma by the new AE antennas contains many toroidal harmonics, contrary to the case of the saddle coils, with which we were able to excite n=1 or n=2 modes (depending on the selected phasing), with the other harmonics accounting for less than 10% of the excited power spectrum. Hence, it is difficult to separate the different harmonics and evaluate the frequency, mode number and damping for each one [3]. This is further complicated by the limited number of (unevenly distributed) pick-up coils available to cover the toroidal cross-section, and by the fact that no internal measurements (via ECE and reflectometry data) of the excited AE spectra have been so far routinely available. Various numerical tools are being assessed to resolve the uncertainty in the n-number determination: DFT, SVD, Wigner and Choi-Williams Transforms, Lomb Periodograms. So far, the most promising method seems that to combine the vacuum antenna excitation spectrum with the numerical tools provided by the “SparSpec” code [4]. This code has been previously used for the analysis of astrophysical data and is now being adapted for routine use on JET data.

First Qualitative Experimental Results

We present here three examples of the first qualitative measurements of the damping rate for low- and medium- to high-n AEs with the new antennas: the n-number spectrum is inferred tentatively from the vacuum antenna excitation spectrum (as estimated at the LCFS).



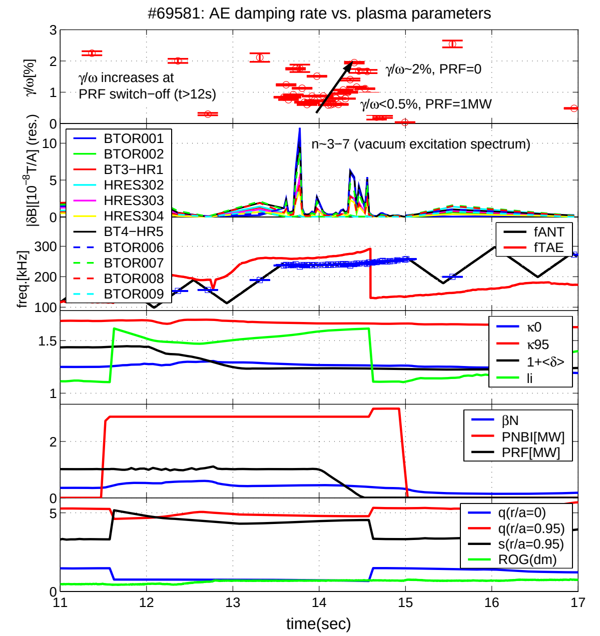


Figure 3. Damping rate measurements for n~1-3 TAEs in ohmic plasmas with low edge elongation.

Figure 4. Damping rate data for n~3-7 TAEs at P_{RF} switch-off for constant plasma parameters and P_{NBI}.

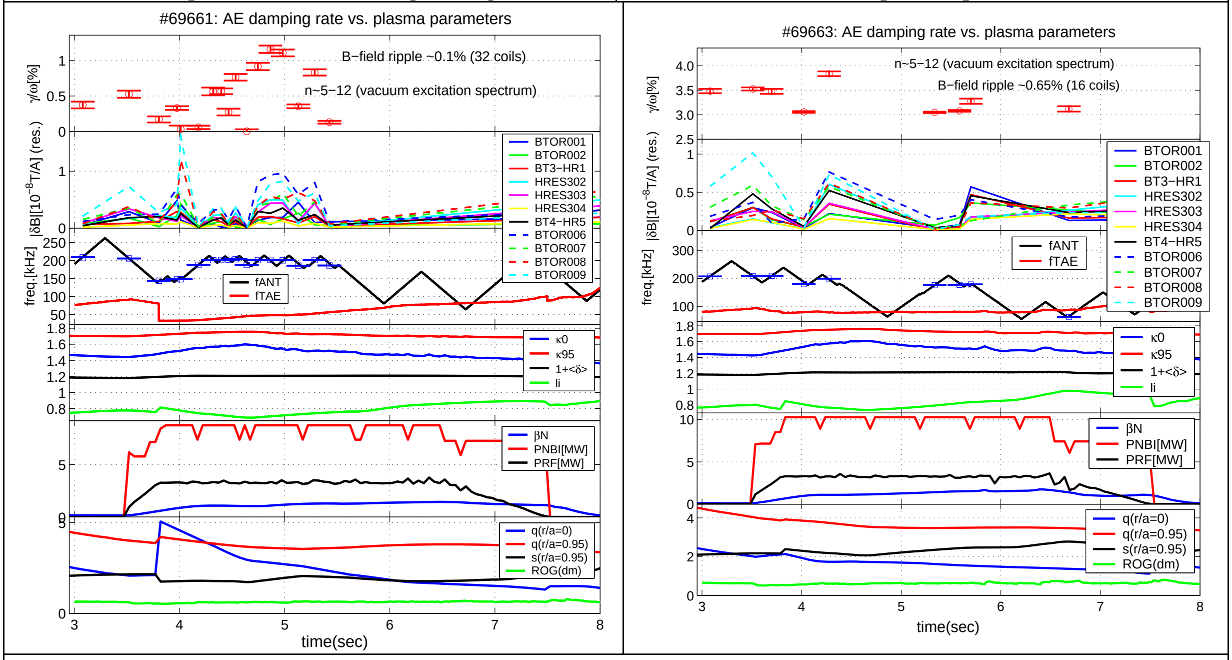


Figure 5. Damping rate measurements for n~5-12 TAEs as function of the B-field ripple in the presence of resonant NBI ions, $v_{\|NBI}\sim v_A/3$: γ/ω increases from γ/ω=0.7% without ripple to γ/ω~3.5% for 0.65% ripple.

As no reliable method for separating the individual toroidal components has been developed yet, the measurements of the damping rate (γ/ω) reported here represent an upper limit to the value for each individual mode number. As an essential verification of the data obtained with the new antennas, fig.3 shows that, for ohmic plasmas with low edge elongation, the damping rate of low-n (n~1-3) TAEs, as measured with the new antennas, is essentially identical to that measured with the old saddle coils [3]. As shown in fig.4, the damping rate γ/ω of n~3-7 TAEs increases linearly with P_{RF} at the ICRF power switch-off for otherwise constant plasma parameters and P_{NBI}. As shown in fig.5, when the fast ion drive is provided by resonant NBI ions with $v_{||NBI}\sim v_A/3$, the damping rate of n~5-15 TAEs increases to $\gamma/\omega\sim3\%$ in the presence of a ~0.65% ripple in the toroidal magnetic field, compared to $\gamma/\omega\sim1\%$ without B-field ripple.

Outlook and Future Work

Despite the fact that the new AE antennas have a small effective area and are rather away from the LCFS, routine measurements of the damping rate for low- and medium- to high-n AEs have been obtained for a variety of JET operating regimes, with real-time tracking of the driven resonances providing tens of individual damping rate data on a single discharge. This is a very promising technical result in view of a possible use of compact active antennas in ITER for burn control applications.

The second set of new AE antennas is to be installed during the forthcoming shutdown: simultaneous use of the two sets is expected to excite a narrower antenna n-spectrum, hence simplifying the damping rate analysis. Moreover, it is expected that internal measurements of the AE spectrum may become more reliable, providing insights for determining the antenna-driven mode structure. Testing of different analysis methods to de-convolve the driven multi-n antenna spectrum is expected to be completed, so that more quantitative measurements of the mode frequency and damping rate for individual toroidal mode numbers will become available. This will also allow a comparison with the measurements of the damping rates for moderate n TAEs that were previously obtained on C-Mod [5].

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