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D. Testa, A. Fasoli, A. Klein, P. Beaumont, R. Bertizzolo, R. Chavan, F. Dolizy,
P. Lavanchy, P. Marmillod, V. Riccardo, S.G. Sanders, J.A. Snipes, J. Thomas,
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First Measurement of the Damping Rate of High-n Toroidal Alfvén Eigenmodes in JET Tokamak Plasmas

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D. Testa[1], A. Fasoli[1], A. Klein[2], P. Beaumont[3], R. Bertizzolo[1], R. Chavan[1],
F. Dolizy[1], P. Lavanchy[1], P. Marmillod[1], V. Riccardo[3], S.G. Sanders[3],
J.A. Snipes[2], J. Thomas[3], P. Titus[2], R. Walton[3], M. Way[3]
and JET EFDA contributors*

[1]CRPP, Association EURATOM – Confédération Suisse, EPFL, Lausanne, Switzerland
[2]MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon
** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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1. INTRODUCTION

After many years of successful operation, the JET saddle coil system was dismantled during the 2004-2005 shutdown. 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: [1]) by fusion generated alphas or other fast particles have toroidal mode numbers in the range $n\sim5-20$. 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 [2].

In this paper we review the antenna design principles and present the first measurements of the frequency and damping rate for $n\sim1-10$ AEs 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.

2. ANTENNA DESIGN PRINCIPLES

The new antenna system has been designed to overcome the technical limitations of the old saddle coils. Eight compact ($NA\sim1m^2$ compared to $NA\sim15m^2$ 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 developed to achieve for n = 5 Toroidal AEs (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 system is 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 the minimum value ~20mm for some optimized plasma shape for the saddle coils. Figure 1 shows one assembly of four antennas, which was installed in JET in 2005 (the second group of four antennas is to be installed in 2007). The full technical commissioning (including plasma operation) started in 2005.

The new antenna system has been in routine operation since January 2007. Damping rate data were obtained for about 1200 discharges, with real-time tracking of the driven plasma resonance on about a third of these, covering all the different JET operating regimes.

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.

3. FIRST QUALITATIVE EXPERIMENTAL RESULTS FOR LOW- TO HIGH-N AES

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 and allowing for an exponential decay of the driven spectrum towards the LCFS (tunnelling effect in vacuum).

As an essential verification of the data obtained with the new antennas, fig.3 shows that, for ohmic plasmas with low edge elongation $\kappa_{95} \sim 1.3$, the damping rate of low-n ($n \sim 1-3$) TAEs, as measured with the new antennas (excitation spectrum ++++) is essentially identical to that measured with the old saddle coils [3]. On the other hand, two general difficulties arise when using excitation spectra that drive a higher n-spectrum ($n \sim 5-20$): the first is related to the much lower antenna-driven $dB \sim 1\times10^{-5}G$ (compared to $dB \sim 3\times10^{-4}G$ for $n \sim 1-3$) achieved at the LCFS, and the second to the accurate determination of the resonant n-spectrum driven in the plasma for a broadband antenna excitation spectrum (fig.2). These difficulties were also experienced in C-mod [4] using similar sized antennas.

Given the large bandwidth of the antenna excitation spectrum, 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 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. So far, the most promising method seems that to combine the vacuum antenna excitation spectrum with the numerical tools provided by the "SparSpec" code [5]. This code has been previously used for the analysis of astrophysical data and is now being adapted for routine use on JET data.

As example of the data obtained for medium-n modes, fig.4 shows that the damping rate γ/ω of $n \sim 3-7$ TAEs increases linearly with P_{RF} at the ICRF power switch-off for 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 $n \sim 5-15$ TAEs increases to $\gamma/\omega \sim 3\%$ in the presence of a ~0.65% ripple in the toroidal magnetic field, compared to $\gamma/\omega \sim 1\%$ without B-field ripple.

4. OUTLOOK AND FUTURE WORK

Routine measurements of the damping rate for low- and medium- to high-n AEs have been obtained for various JET operating regimes, with real-time tracking of the driven resonances providing tens of individual damping rate data on a single discharge. This result has been obtained using compact antennas with a small effective area and located rather away from the LCFS. 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. We are also planning to use a different set of amplifiers with different phasing for this second set, so as to approach the regimes where active control of burning plasmas could be achieved. It is also expected that internal measurements of the AE spectrum may become more reliable, providing further 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 [4].

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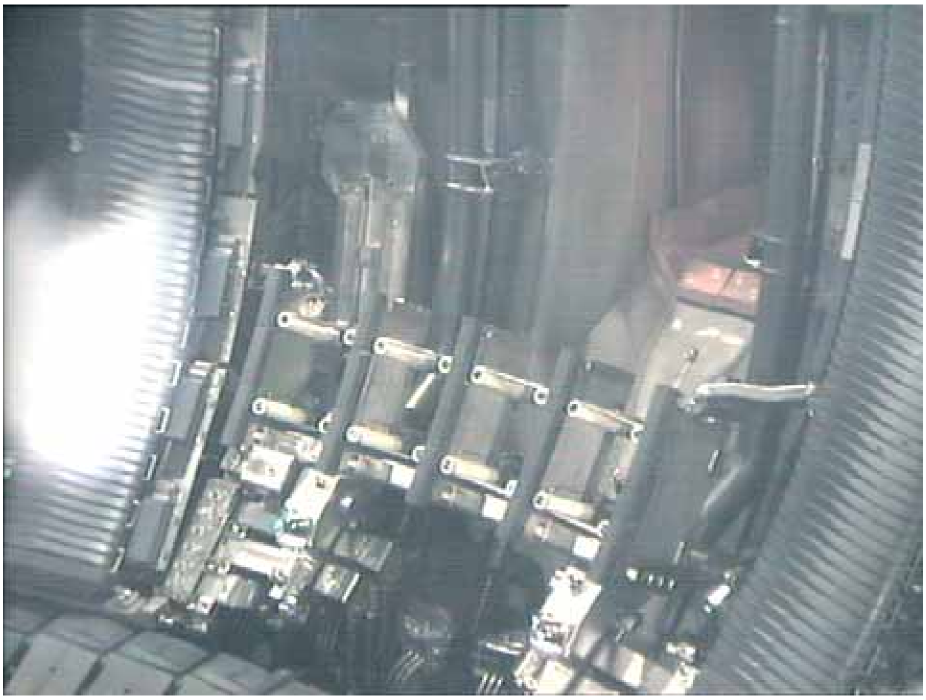

Figure 1. View of one group of four AE antennas as installed in vessel during June 2005.

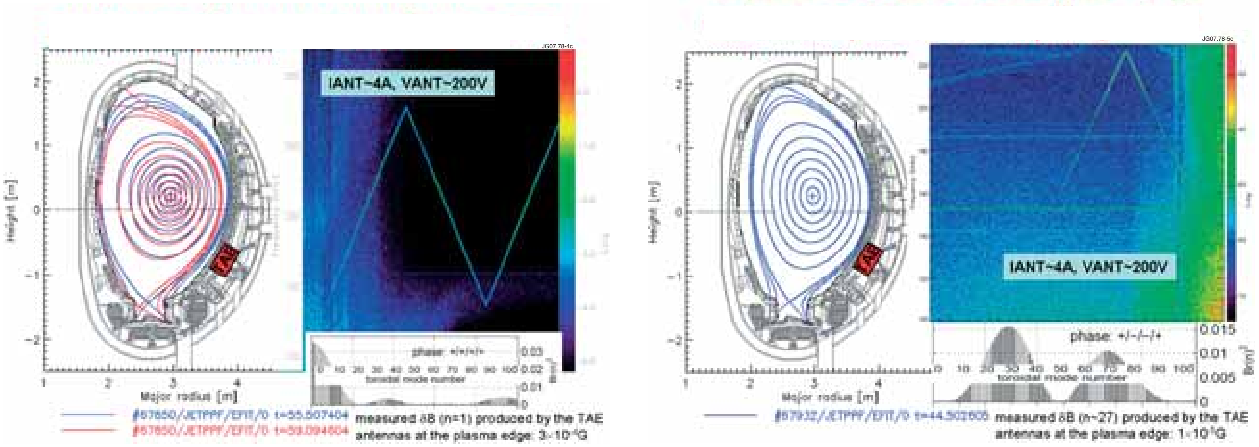

Figure 2. Nominal vacuum and plasma excitation spectra using different antenna phasing configurations. A value of $dB\sim3\times10^{-4}$G is obtained for the ++++ excitation structure (low−n), whereas $dB\sim1\times10^{-5}$G is obtained for the +—+ excitation structure (nominal n-spectrum centred around n ~ 25 with HFWM~10 at the antenna mouth).

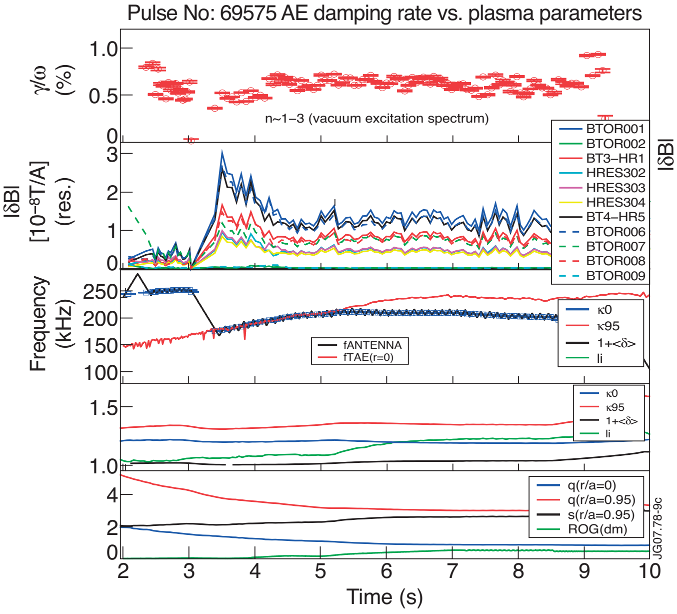

Figure 3. Damping rate measurements for n~1-3 TAEs in ohmic plasmas with low edge elongation.

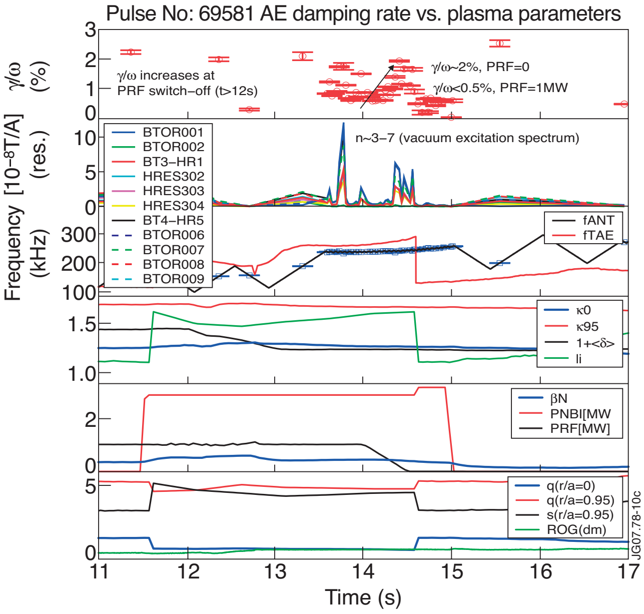

Figure 4. Damping rate data for n~3-7 TAEs at P_{RF} switch-off for constant plasma parameters and P_{NBI}.

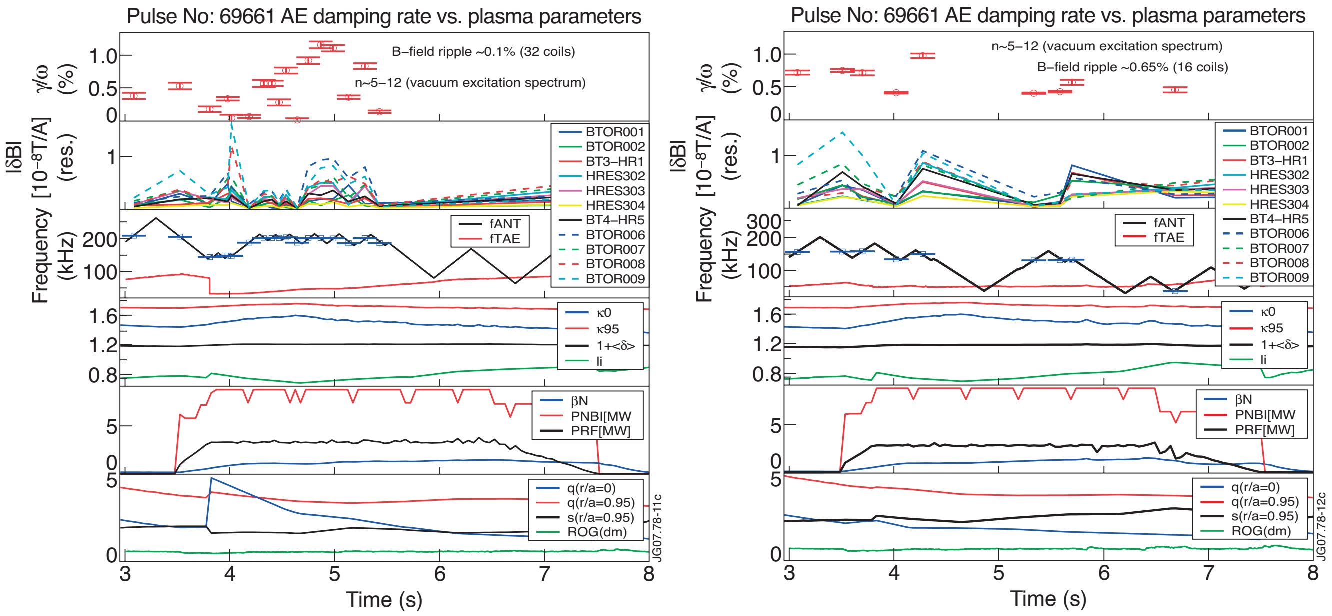

Figure 5. Damping rate measurements for n~5–12 TAEs as function of the B-field ripple in the presence of resonant NBI ions, $v_{||NBI} \sim v_A/3$*: g/w increases from γ/ω=0.7% without ripple to γ/ω~3.5% for 0.65% ripple.*