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

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

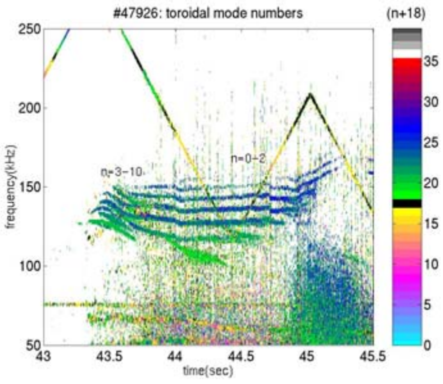
INTRODUCTION

After many years of successful operation, the JET saddle coil system was dismantled during the 2004-2005 shutdown [1]. A new antenna system was installed to replace it and excite MHD modes in the Alfvén frequency range, with similar operational capabilities [2].

Why Study Alfvén Waves?
Why Replace the Saddle Coils?

1. fusion-born alpha particles (α's) resonate with Alfvén Waves (AWs) if $\omega=k_{||}\upsilon_A$
2. AW spectrum unstable if large-enough free energy in the fast ion pressure gradient
3. an unstable AW spectrum can lead to direct α's losses, possibly quenching the ignition process and damaging the first wall
4. due to their geometry, the saddle coils only drive low toroidal mode numbers, |n|<2
5. ITER predictions [3]: most unstable modes have n~5-20 (already observed in JET)

➔ therefore difficult to extrapolate directly low-n results to burning plasmas and ITER



ANTENNA DESIGN PRINCIPLES AND OPERATIONAL RESULTS

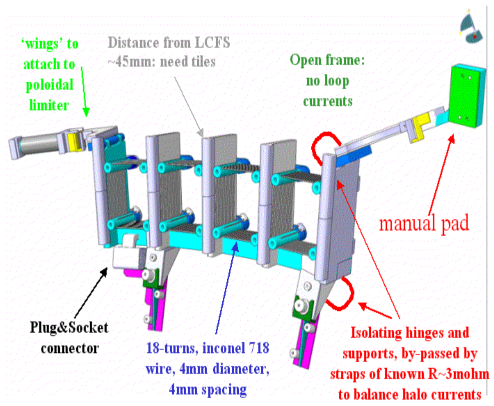
- total halo current integrated over the antenna surface = 90kA (I_{p0}=6MA, I_{HALO}/I_{p0}=30%, TPF=1.4)
- loop voltage at disruptions: 800V/6MA, ~25V at each bellow (avoid close toroidal path of low R)
- radiative power up to 150kW/m^2 for >30sec; energy blip at disruptions ~ 1MJ/m^2 over <1ms

➔ antennas mounted on an open frame, to avoid a closed path for disruption-induced currents

➔ frame attached to poloidal limiter via 3mΩ resistive straps to optimise the load distribution

➔ antennas and frame protected by CFC tiles mounted on private mini-limiters

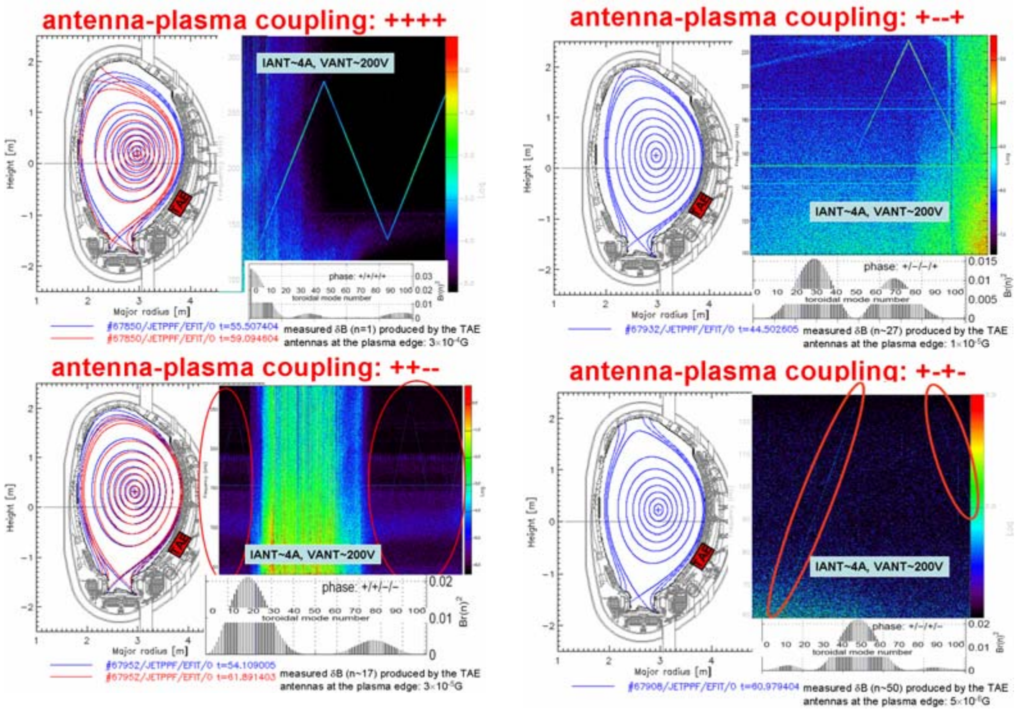
- small compact antennas: 18 turns, NA~1m^2 (saddle coils: NA~15m^2)
- antenna-plasma distance: 60mm to LCFS (saddle coils: 20mm to LCFS)
- two groups of four antennas each at opposite toroidal locations to control driven n-spectrum



Close-up showing various engineering details.

AE antennas as installed in-vessel in June 2005.

- excited n-spectrum: easily up to n~30 for different antenna phasing configurations

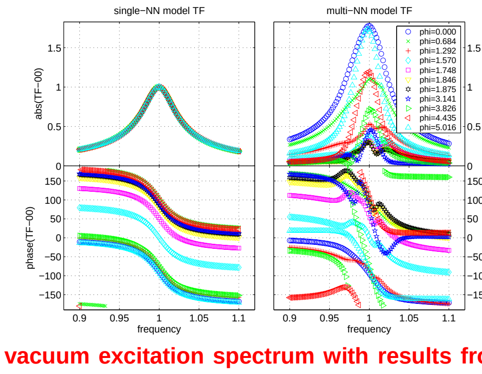


Calculated (vacuum) excitation spectra obtained using different antenna phasing configurations.

PROBLEMATIC DETERMINATION OF TOROIDAL MODE NUMBERS

- saddle coils: almost pure n=1/n=2 spectrum, other harmonics <10% in power spectrum
- new antennas: (vacuum) excited spectrum is multi-harmonics, with typical HFWM>10
- limited number of pick-up coils, no reliable internal measurements of AE mode structure
- **hence very difficult to separate precisely the different harmonics and evaluate the frequency and damping rate for each one**

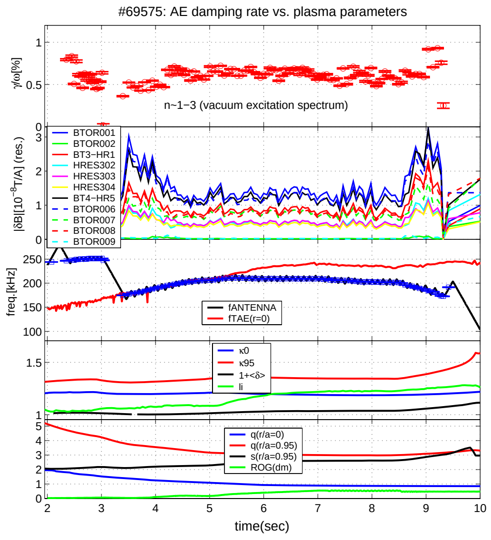
➔comparison (see figure): predicted TAE signal at each pick-up coil for one mode (n=5, ω_n=1, γ_n=2%) and five modes (n=3-7, closely spaced in frequency: $\Delta\omega_n$=2%, γ_n[%]=0.2-1.0)



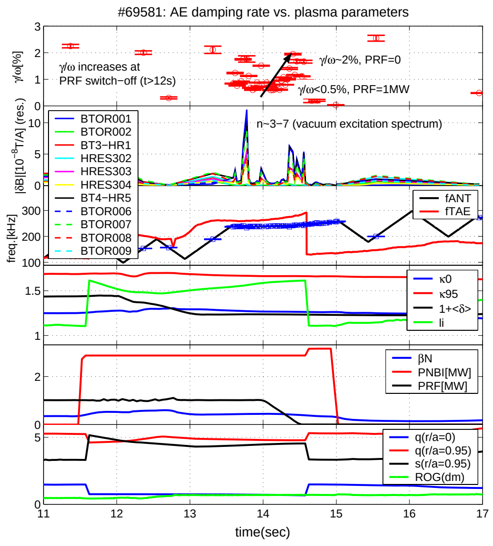
- **most promising method so far: combine vacuum excitation spectrum with results from "SparSpec" code [4] (previously used for the analysis of astrophysical data)**

FIRST QUALITATIVE EXPERIMENTAL RESULTS

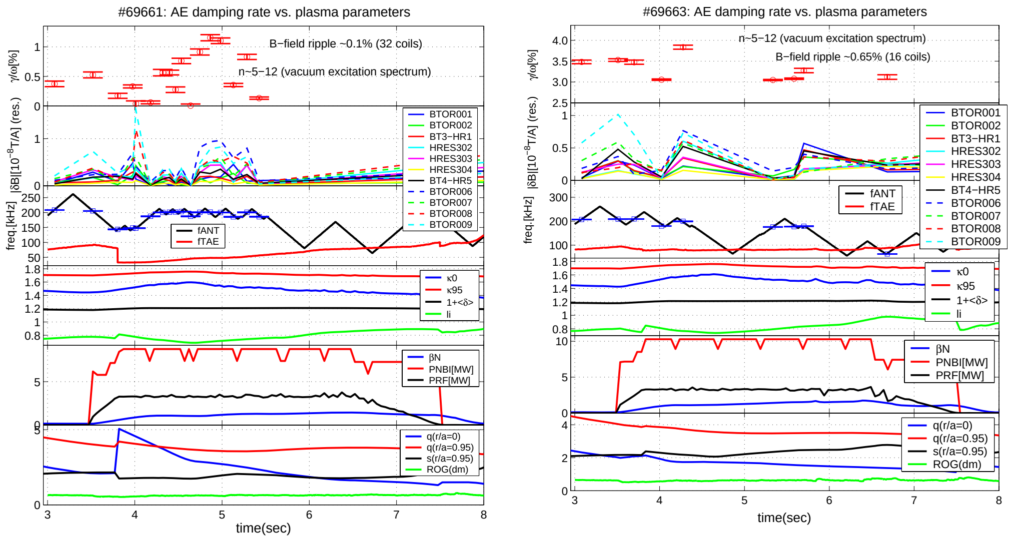
- n-number spectrum tentatively inferred from the vacuum antenna excitation spectrum
- qualitative measurements of the damping rate to be considered as an upper limit to the value for each individual n-component
- **benchmark against saddle coils data: measured γ/ω for low-n TAEs in ohmic plasmas with low edge elongation is the same ➔ essential verification!**



For ohmic plasmas with low edge elongation, the damping rate of low-n (n~1-3) TAEs, as measured with the new AE antennas, is identical to that measured with the old saddle coils



At the ICRF power switch-off, the damping rate γ/ω of n~3-7 TAEs increases linearly with P_{ICRF} for otherwise constant plasma parameters (NBI power, edge elongation and magnetic shear).



when the fast ion drive is provided by resonant NBI ions with $v_{||NBI}$~v_A/3, the damping rate of n~5-15 TAEs increases to γ/ω~3% in the presence of a ~0.65% B-field ripple, compared to γ/ω~1% without B-field ripple. These data provide examples of a direct estimate of the fast ion drive to these modes.

CONCLUSIONS

- first measurement s of the damping rate of AEs with n~1-30 with new antennas in JET
- **routine real-time mode detection and tracking even with small antennas located far away from LCFS ➔ possible use in ITER for burn control applications?**
- problematic determination of n's because of complex excitation spectrum
- various numerical tools being assessed and developed for accurate n-spectrum separation

OUTLOOK AND FUTURE WORK

- second set of new antennas to be installed during the forthcoming shutdown: simultaneous use of the two sets (located at toroidally symmetric positions) is expected to provide a narrower antenna excitation spectrum, hence possibly simplify the damping rate analysis
- internal measurements of the AE mode structure may become more reliable, hence providing insights for determining the antenna-driven mode structure
- testing of the 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
- comparison with previous results for medium-n TAEs from Alcator C-mod [5]

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