Exploration of Alfvén Eigenmode physics via active antenna excitation in JET Deuterium, Tritium, and DT plasmas

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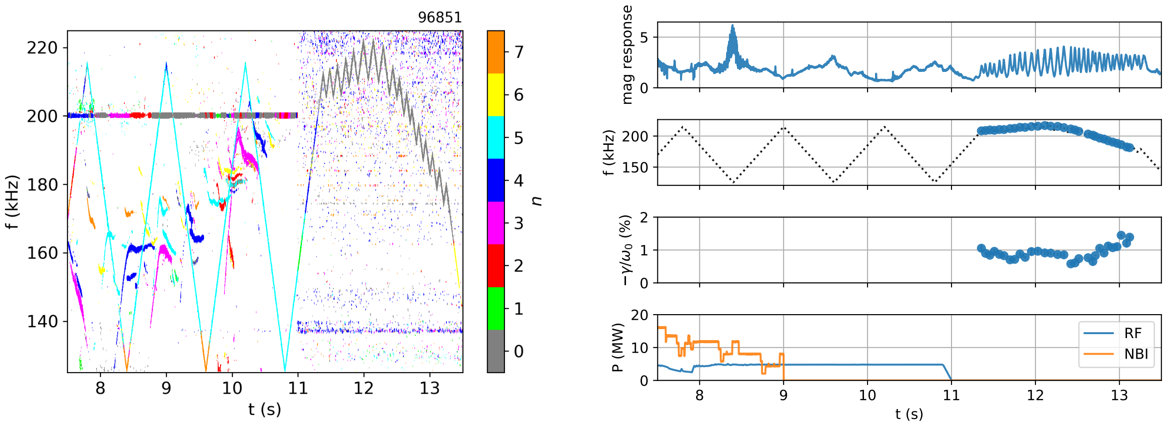
While the growth rate of destabilized Alfvén Eigenmodes (AEs) can often be difficult to assess from experimental measurements, the total damping rate of stable AEs is readily measured in JET tokamak plasmas by the Alfvén Eigenmode Active Diagnostic (AEAD) [1]: two toroidal arrays of four antennas each [2] are independently powered and phased to resonantly excite stable AEs with toroidal mode numbers $|n| < 20$ [3]. Fourteen fast magnetic probes measure the plasma response; from this, the resonant frequency f_0, damping rate $\gamma < 0$, and n are assessed [4] and used to validate theory and modeling, improving projections to future tokamaks.

A novel measurement of TAE stability transition: destabilized to stabilized

In preparation for the JET DT campaign, scenario development for the observation of alpha-driven instabilities was pursued [5], and the synergy of Neutral Beam Injection (NBI) and Radio Frequency (RF) heating was modeled and analyzed in depth for JPN 96851, a Deuterium plasma. In this pulse, $n = 1-7$ Reverse Shear AEs (RSAEs) were destabilized from $t \approx 7.5-11$ s (see Fig. 1a), during ∼10 MW of NBI and ∼5 MW of RF heating (see Fig. 1b). During this time, the AEAD scanned in frequency, $f \approx 125-215$ kHz, although not resonating with the unstable RSAEs. After RF turned off at ∼11 s, the AEAD tracked a stable AE in real-time from ∼11.3 − 13 s, as seen in the spectrogram of Fig. 1a. The AE magnetic response, resonant frequencies $f_0 \approx 210 \rightarrow 180$ kHz, and normalized damping rates $\gamma/\omega_0 \approx -1\%$ are shown in Fig. 1b. From the continuity in AE frequency, this appears to be a novel observation of an AE stability transition, from unstable to stable.

Two time-slices, 10.6 s and 11.3 s, were modeled with the hybrid kinetic-MHD code NOVA-K [6–8], using plasma profiles from TRANSP and safety factor profiles from EFIT [9]. The



(a) (b)

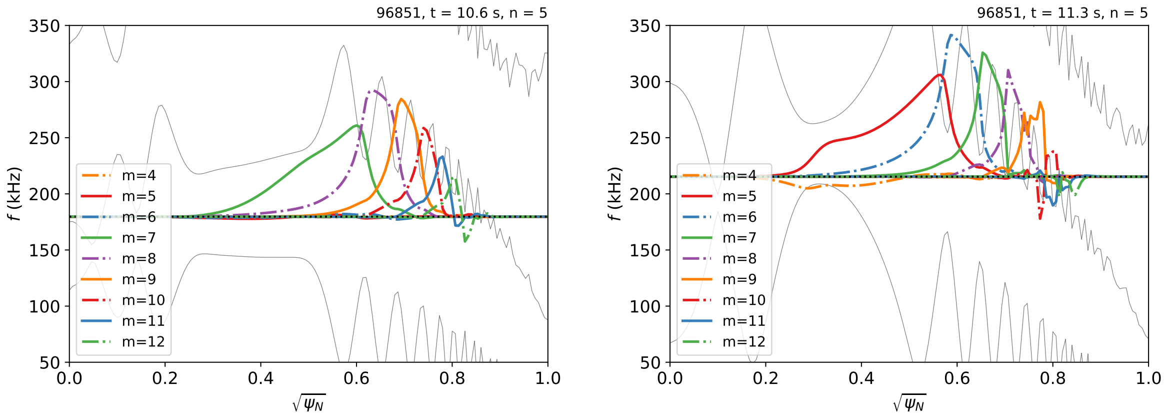
Figure 1: (a) Spectrogram with toroidal mode number analysis for JPN 96851. (b) Magnetic response, frequency, and normalized damping rate of the measured stable AE, along with NBI and RF heating.

q-profiles are evaluated to have reverse shear at both times; this is consistent with RSAEs at 10.6 s, but not for 11.3 s, when sawteeth in the electron temperature are observed. Thus, the q-profile was shifted down, $\Delta q = -0.2$, to achieve $q < 1$ for the latter time. Toroidal mode numbers $n = 4-6$ were modeled since they are the last-appearing unstable modes in Fig. 1a; NOVA-K frequencies and damping rates are given in Table 1. The $n = 4, 5$ Toroidicity-induced AEs (TAEs) match well at both times: $f_0 \approx 180$ kHz at 10.6 s (i.e. at the maximum/end of the RSAE's frequency sweep) and ~205 – 215 kHz at 11.3 s, consistent with experiment. Alfvén continua and poloidal mode structures for the $n = 5$ mode are shown in Fig. 2.

Table 1: Eigenfrequencies f_0 and normalized damping rates γ/ω_0 from NOVA-K for simulated $n = 4-6$ TAEs at two times. See Fig. 2 for the $n = 5$ eigenmode structures.

f_0 (kHz) / $-\gamma/\omega_0$ (%)	$n = 4$	$n = 5$	$n = 6$
t = 10.6 s	182 / 0.5	180 / 0.9	187 / 1.2
t = 11.3 s	203 / 1.0	215 / 1.1	217 / 2.1

NOVA-K calculates the damping rate for the $n = 5$ TAE to be $\gamma/\omega_0 \approx -1\% \pm 0.1\%$ for both times; this is inconsistent with the unstable mode at 10.6 s, but matches the experimental measurement well at 11.3 s. Dominant contributions come from radiative (0.7%), electron Landau (0.1%), and continuum damping (0.1%), with uncertainties ~0.1%. We see the mode's intersection with the continuum around $\sqrt{\psi_N} \approx 0.8$ in Fig. 2, as well as the closeness of the eigenmode to the continuum near $\sqrt{\psi_N} \approx 0.3$ in Fig. 2. NOVA-K even calculates some damping from the RF-accelerated fast ions (0.2%). The discrepancy in stability at 10.6 s is yet to be resolved.



(a) (b)

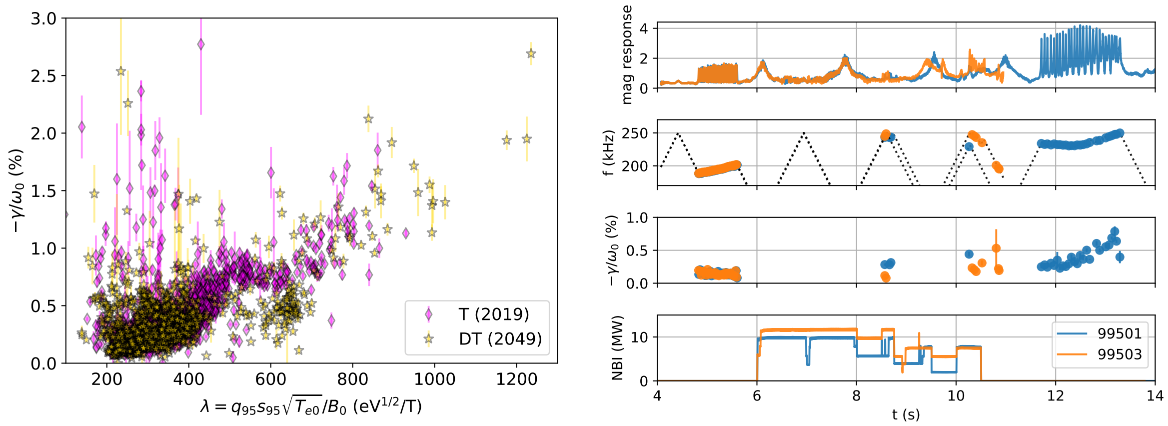
Figure 2: NOVA-K Alfvén continua and $n = 5$ eigenmodes for JPN 96851 at (a) 10.6 s and (b) 11.3 s. In (b), the safety factor profile was lowered: $q \to q - 0.2$. ψ_{N} is the normalized poloidal flux.

A database of stable AEs in JET T and DT plasmas

Over 2000 stable AEs were measured in each of the recent JET T and DT campaigns, in more than 100 and 200 plasma discharges, respectively. A new high-frequency filter was also built for these campaigns, $f \in 165-330$ kHz, which allowed stability measurements of high-frequency TAEs (above the previous 250 kHz limit) and even of Ellipticity-induced AEs (EAEs). In fact, in the T campaign, over 10% of stable AE observations had frequencies >250 kHz.

As seen in Fig. 3a, the normalized damping rate increases with the so-called non-ideal parameter λ [10], which includes kinetic effects and indicates radiative damping of the stable AEs, for both T and DT plasmas, with correlation coefficients >0.6. This has also been seen before in D plasmas [11]. Strong correlations are also found with the edge safety factor q_{95} and edge magnetic shear s_{95} individually, also indicating continuum and radiative damping. Further trends in the database will be investigated in the near future.

From the DT database, discharges JPN 99501 and 99503 have been selected for further analysis. These experiments aimed to destabilize AEs via bump-on-tail (BOT) instabilities in the alpha population. The magnetic responses, resonant frequencies, and damping rates of stable AEs are shown in Fig. 3b, along with NBI modulation. Of particular interest are the resonances at $t \approx 8.5$ s with frequencies $f_0 \approx 240-250$ kHz and damping rates $-\gamma/\omega_0 \approx 0.1\%-0.3\%$. Preliminary NOVA-K analyses suggest that these are stable, edge-localized ($\sqrt{\psi_{\mathrm{N}}} > 0.6$) EAEs dominated by continuum and electron Landau damping, but having little interaction with alphas (0.02%), although the BOT has not yet been simulated. Similar edge EAEs with low damping rates have been measured before [11], and additional analyses are underway.



(a) (b)

Figure 3: (a) Normalized damping rate vs non-ideal parameter λ for stable AE measurements during the T and DT campaigns (number of data points in parentheses). (b) Magnetic response, frequency, and normalized damping rate of stable AEs, along with NBI heating, for DT plasmas JPN 99501 and 99503.

In summary, NOVA-K has reliably identified stable AEs in two novel scenarios: a stability transition and DT plasmas with alpha bump-on-tail instabilities; in these cases, radiative, continuum, and electron Landau damping are found to be dominant.

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