Investigations of Alfvén Eigenmode stability via active antenna excitation in JET Hydrogen, Deuterium, Tritium, DT, and Helium plasmas

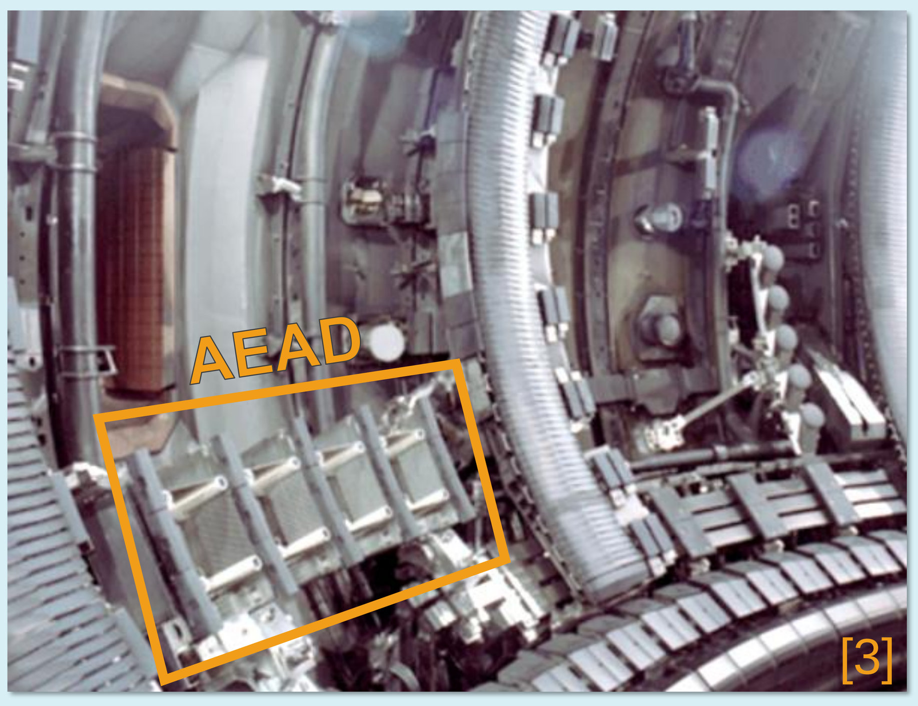
RA Tinguely[1], M Porkolab[1], S Dowson[2], PG Puglia[3], J Garcia[3], A Fasoli[4], J Gonzalez-Martin[5], YeO Kazakov[6], M Podestà[7], and JET Contributors*

[1]MIT PSFC, USA [2]CCFE, UK [3]CEA, France [4]EPFL SPC, Switzerland
[5]U Seville, Spain [6]LPP-ERM/KMS, Belgium [7]PPPL, USA

*See author list of "Overview of T and D-T results in JET with ITER-like wall", C.F. Maggi et al. to be published in *Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference* (London, UK, 16-21 Oct 2023)

Introduction

- The drive of Alfvén Eigenmodes (AEs) by DT-fusion alphas and their resulting transport could greatly impact the performance of future burning plasma experiments, like ITER, SPARC, or FPPs.
- Although many past experiments have explored AE stability, open questions remain, especially on exact AE stability threshold conditions.
- In JET, eight in-vessel antennas actively excite *stable* AEs [1], from which their frequencies f_0, toroidal mode numbers n, and net damping rates $\gamma < 0$ are assessed [2].
- Thousands of AE stability measurements were collected in hundreds of JET plasmas by the Alfvén Eigenmode Active Diagnostic (AEAD) during the recent H, D, T, DT, and He campaigns; main results are presented in this work.



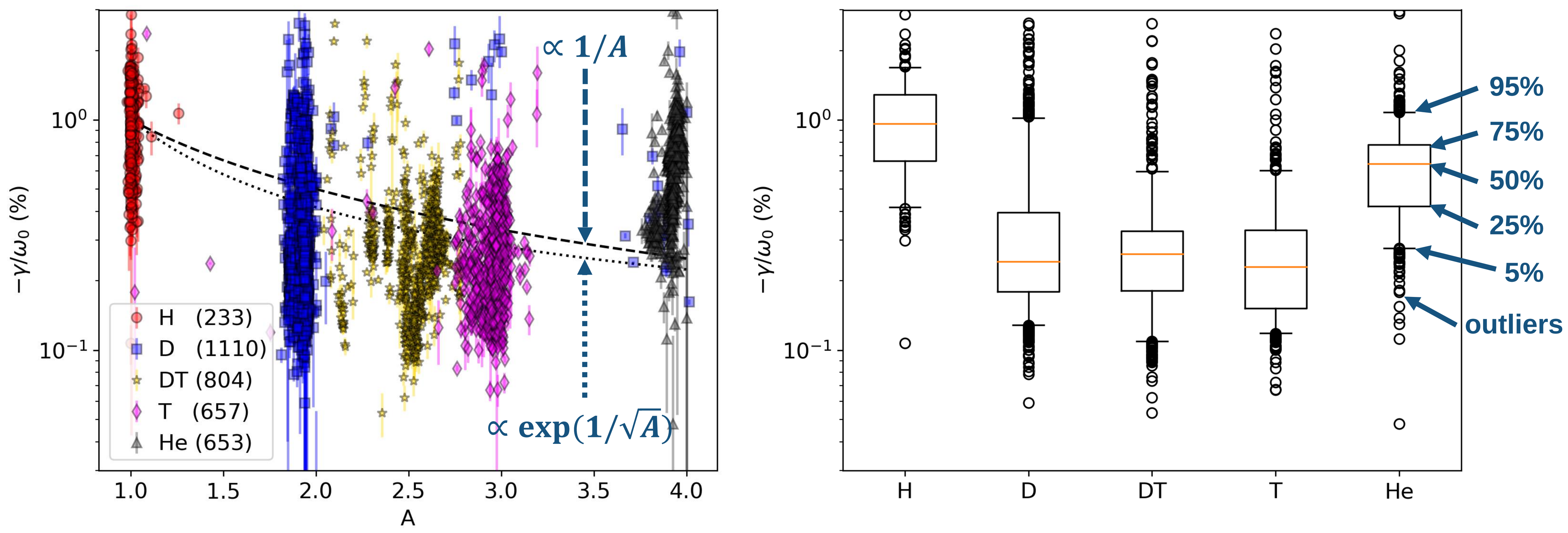
4 x 2 antennas

10 A current

n<20 phasing

Database analyses across H, D, T, DT, and He JET plasmas

- First database of AE stability spanning all four ion species (mass numbers $A = 1-4$)
- Normalized damping rates decrease with A for Hydrogenic plasmas, but increase for Helium

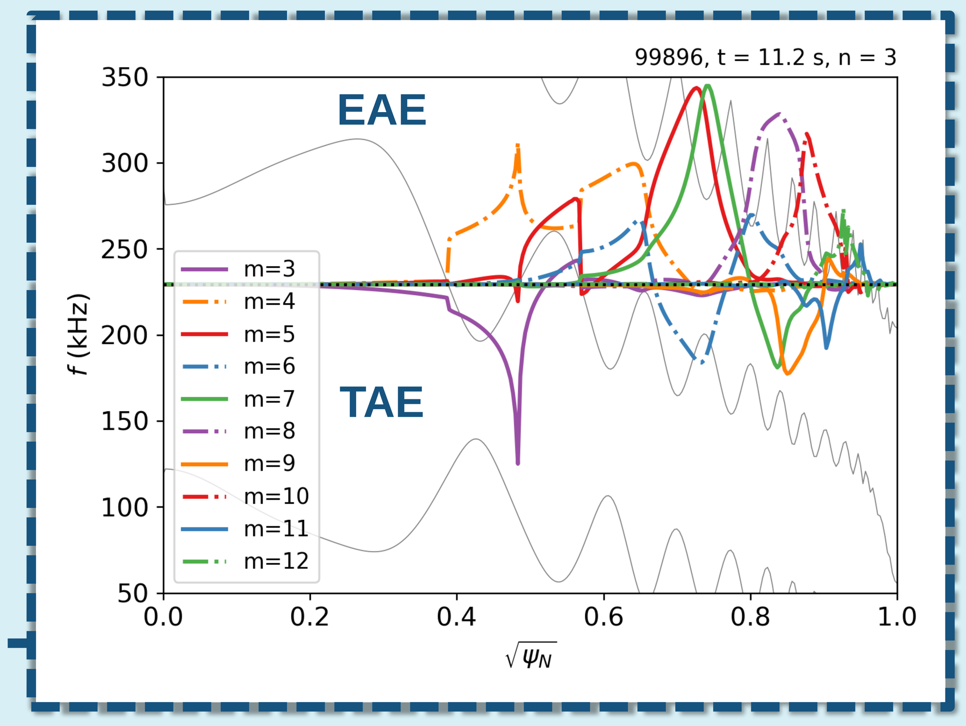


Left: Normalized damping rate vs mass number (number of data points in parentheses). **Right:** Box plots of the same data.

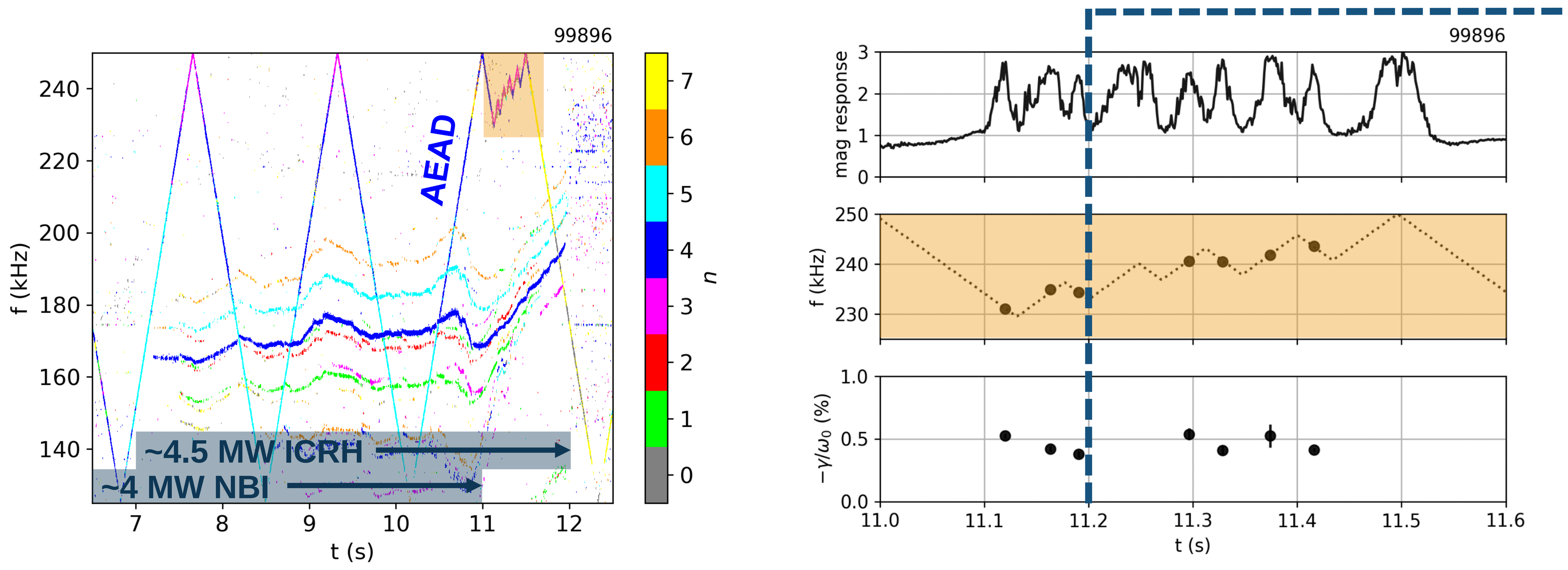
- Previous works identified only inverse trends $-\gamma/\omega_0 \propto 1/A$ [4] and $\exp(1/\sqrt{A})$ [5]
- ➢ Dominant radiative damping $-\gamma/\omega_0 \propto \exp(1/\rho_i) = \exp(Z/\sqrt{A})$ explains this He "anomaly"
- ➢ Consistent with strong correlations with non-ideal parameter $\lambda = q_{95}s_{95}\sqrt{T_{e0}}/B_0$ [6]

Simultaneous measurements of stable and destabilized AEs in JET

- JPN 99896: 50/50 DT plasma, $B_0 \sim 2.8$ T, $I_p \sim 1.9$ MA, $n_{e0} \sim 4\mathrm{e}19\ \mathrm{m}^{-3}$, $T_{e0} \sim 6$ keV [7]
- AEAD tracks a high-frequency $n = 3$ AE: $f_0 \sim 230-250$ kHz, $-\gamma/\omega_0 \sim 0.4\% \pm 0.1\%$
- ➢ Linear code NOVA-K [8-10] identifies an edge EAE with dominant electron Landau damping



$n = 3$ Alfvén continua (lab frame) and mode structure.



Left: Spectrogram with toroidal mode number analysis. **Right:** Stable AE magnetic resonances, frequencies, and damping rates.

- Previously observed in D plasma, during three-ion-heating (D-DNBI-He3) experiments [11]
- Unstable $n = 3-5$ TAEs and a stable $n = 6$ mode with $-\gamma/\omega_0 \sim 2\% \pm 1\%$ [12]
- ➢ NOVA-K → radiative damping (-4.8%) dominates drive from ICRH ($+2.3\%$)
- ➢ Nonlinear hybrid kinetic-MHD code MEGA [13] → impressive agreement across *all* modes

Conclusions

- A comprehensive database of AE stability indicates the dominance of radiative damping, and scaling $-\gamma/\omega_0 \propto \exp(Z/\sqrt{A})$, across JET H, D, T, DT, and He plasmas.
- ➢ AEs could be more easily destabilized in D/T plasmas than similar H/He plasmas, which should be carefully considered in operations of future burning plasma tokamaks.
- Linear code NOVA-K shows impressive agreement with experimental AE damping rates, but only nonlinear code MEGA accurately captures *both* driven and damped AEs.
- ➢ Validation of simulations with experimental measurements from both core and edge-localized AEs gives confidence in extrapolations to future fusion devices.

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