Exploration of Alfvén Eigenmode physics via active antenna excitation in JET deuterium and hydrogen plasmas

R.A. Tinguely[1] P. Puglia[2], N. Fil[3], M. Porkolab[1], S. Dowson[3], D. Douai[4], R. Dumont[4],
A. Fasoli[2], M. Fitzgerald[3], S.E. Sharapov[3], and JET Contributors[†]

[1] *Plasma Science and Fusion Center, MIT, Cambridge, MA, USA*

[2] *EPFL, Swiss Plasma Center, CH-1015 Lausanne, Switzerland*

[3] *Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, UK*

[4] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

[†] *See author list of J. Mailloux et al "Overview of JET results for optimising ITER operation" to be published in Nuclear Fusion, IAEA FEC special issue (2021)*

The stability of Alfvén Eigenmodes (AEs) in tokamak plasmas is determined by various drive and damping mechanisms. If destabilized by populations of fast ions (FIs) such as alphas, AEs can then increase FI radial transport, which is undesirable in future fusion devices like ITER. In JET, the Alfvén Eigenmode Active Diagnostic (AEAD) [1, 2] scans in frequency to resonate with *stable* AEs. The eight toroidally spaced, in-vessel antennas are independently phased [3] to probe different toroidal mode numbers n: low vs high, even vs odd, and positive vs negative. By synchronously detecting data from fast magnetic coils, the AE net damping rate $\gamma < 0$ is assessed along with the resonant frequency $\omega_0 = 2\pi f_0$ and n. These are then compared against theory and simulation, improving projections to future burning plasma operations.

Database studies of AE stability in H, D, and T plasmas

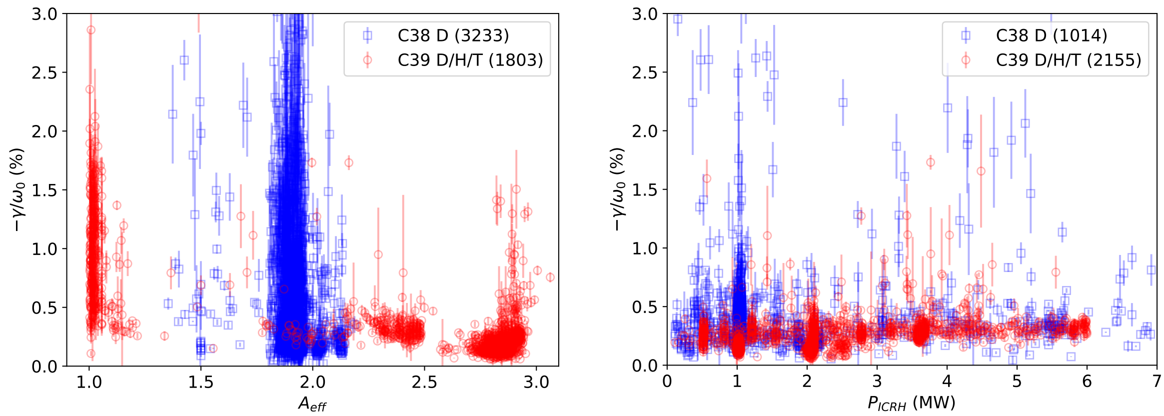
Over the past two years, the upgraded AEAD has been operated on nearly a thousand JET plasma discharges, measuring thousands of stable AE resonances. Analyses of data collected during the 2019-2020 JET C38 campaign (D plasmas) has been reported extensively [4–6]. Here, for the first time, we report the AE stability database assembled for the 2020-2021 JET C39 campaign (D/H/T plasmas), during which the AEAD measured ∼3000 stable AEs in ∼100 pulses. This database is somewhat smaller than that for the C38 campaign due to the C39 campaign's limited duration and scope. Distributions of plasma parameters for the C39 database are shown in Table 1; the ranges are slightly narrower than those in the C38 database (see Table 3 in [4]). Still, general trends of higher damping with increasing edge safety factor, magnetic shear, and non-ideal effects are observed and linked to continuum and radiative damping.

Importantly, the JET C39 campaign involved a transition from D to H to T plasmas. Thus, stable AEs were measured for a variety of isotopes and their ratios. Note that the H data, in

Table 1: Ranges of plasma parameters for the JET C39 (D/H/T) campaign stable AE database.

Parameter	I_p	B_0	n_{e0}	T_{e0}	P_{RF}	q_0	q_{95}	s_{95}	κ
Units	(MA)	(T)	(10^{19} m^{-3})	(keV)	(MW)				
5th %tile	1.10	1.64	1.95	1.03	0.00	0.78	2.72	3.22	1.32
95th %tile	1.79	2.28	3.94	2.04	4.82	1.00	4.73	5.30	1.63

particular, could benefit ITER's pre-fusion-power operation in H/He plasmas. The normalized damping rate γ/ω_0 is shown for all C38 and C39 data in Fig. 1a. Here, the effective mass number is calculated as $A_{\rm eff} = \sum_{\rm i} A_{\rm i} n_{\rm i}/n_{\rm e}$, with $A_{\rm i}$ the mass number of each ion species and $n_{\rm i}, n_{\rm e}$ the ion and electron densities, respectively. The isotope fractions are determined from spectroscopic measurements, and data are restricted to $\sum_{\rm i} Z_{\rm i} n_{\rm i}/n_{\rm e} \in 1 \pm 0.1$, with $Z_{\rm i}$ the atomic number and assuming a fully ionized plasma. In addition to H, D, and T, ^{3}He and ^{4}He are also considered.



(a) (b)

Figure 1: Normalized damping rate vs (a) effective mass number and (b) ICRH power for data collected during the JET C38 (D, squares) and C39 (D/H/T, circles) campaigns. Data in (b) are limited to only ICRH power and uncertainties $\Delta\gamma/\omega_0 < 0.5\%$. The total number of data points is given in parentheses.

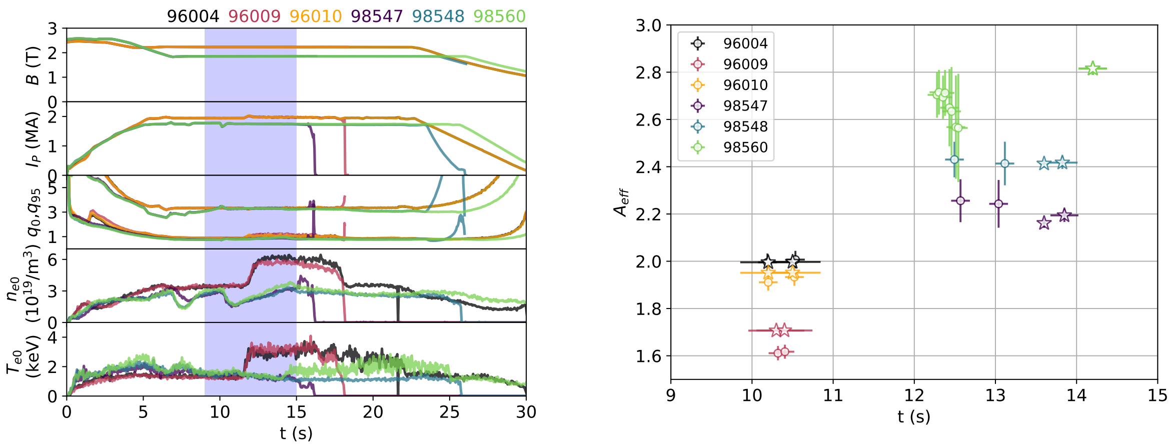
While no clear trend is seen in the C38 data (clustered at $A_{\rm eff} \approx 2$), the damping rate is observed to decrease with increasing mass number in the C39 data. This was also seen previously in JET for low-n AEs ($|n| \leq 2$) [7,8] and was attributed to AE mode conversion to kinetic Alfvén waves, confirmed by gyrokinetic simulations. The opposite trend, i.e. $\gamma/\omega_0 \propto A_{\rm eff}$, was found for medium-$n$ AEs ($|n| \geq 3$) [8]. Discrimination by n for this C39 data is left to future work.

One improvement of the C39 database compared to the C38 database is that twice as many stable AEs were observed at significant ICRH power. One explanation for this is that ICRH and NBI were often used in conjunction during the C38 campaign, thereby obscuring AE resonances in the noisy magnetics signal; however, no NBI was used during the C39 campaign. All data are shown in Fig. 1b. A linear correlation - weighted by the inverse variance $(\Delta\gamma/\omega_0)^{-2}$ - indicates a weak but *positive* trend: $r_w(-\gamma/\omega_0, P_{ICRH}) = 0.25$. This is counterintuitive as increased P_{ICRH} would be expected to increase the FI drive. It is also opposite to the trend found in the C38 data [6]. However, there could be conflating factors, such as increased temperatures and ion Landau damping or minimal interaction of FIs and edge-localized AEs probed by the AEAD.

Isotope ratio measurements from stable AEs

Active MHD spectroscopy utilizing the AEAD has been demonstrated before on JET [9, 10]. Of particular interest is measuring the isotope ratio, which will be of utmost importance in the upcoming JET DT campaign as well as in future DT fusion devices. The AEAD is well-suited for this as the Alfvén speed - and hence the AE frequency - depends on the effective mass via $v_A \propto A_{eff}^{-1/2}$. Moreover, destabilization by FIs is not required to make this measurement, making the AEAD essential if alpha drive is insufficient to destabilize AEs in JET DT plasmas.

Time traces of six plasma discharges, all part of a dedicated JET experiment on isotope ratio measurements, are shown in Fig. 2a. The magnetic geometries are well-reproduced in the pulses, as evidenced by the toroidal magnetic field, plasma current, and central/edge safety factors. Two sets of three pulses were used to assess A_{eff} in H-D and H-T plasmas, respectively. The densities and temperatures are similar within those sets, especially during $t \approx 9 - 15$ s (shaded).



(a) (b)

Figure 2: (a) Six pulses during which the isotope ratio was deduced from stable AEs (shaded region). (b) Effective mass numbers estimated from AE frequencies (circles) and divertor spectroscopy (stars).

Figure 2b compares A_{eff} values calculated from divertor spectroscopy (stars) and from resonant AE frequencies in combination with global plasma parameters (circles) [11]. Note that the spectroscopic and stable AE measurements are not always simultaneous. Even then, good agreement is observed between the two methods, and most data agree within error bars or at least ∼10% uncertainty. Because the spectroscopic measurement comes from the edge plasma, this likely indicates that the stable AEs are also edge-localized and not in the core. Nevertheless, this nicely demonstrates that the AEAD can make a complementary measurement of the isotope ratio in ongoing T and upcoming DT experiments.

Strategy for AEAD operation in JET DT plasmas

Over the past two years, our team has mapped the operational space of the AEAD with the aim of optimizing its performance in the upcoming JET DT campaign. The probability of stable AE detection has been found to decrease with increasing I_{p} and NBI and ICRH power [4]. The AEAD also exhibits reduced efficiency in X-point vs limiter magnetic configurations [5] as well as in H-mode [6]. Yet, novel measurements indicate that the AEAD can overcome these limitations: A marginally stable EAE was tracked in real-time during ∼25 MW of external heating [6], and AEs were monitored from destabilization through stabilization in dedicated JET energetic particle experiments [12]. Importantly, simulations predict that the alphas may only marginally destabilize TAEs *outside* the core of DT plasmas [13], where the AEAD has fortunately demonstrated the best accessibility and successful AE measurements.

Acknowledgments

This work was supported by US DOE DE-SC0014264, has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] A Fasoli *et al* (1995) Phys. Rev. Lett. **75** 4 645-648
[2] T Panis *et al* (2010) Nucl. Fusion **50** 084019
[3] P Puglia *et al* (2016) Nucl. Fusion **56** 11 112020
[4] RA Tinguely *et al* (2020) Plasma Phys. Control. Fusion **62** 11
[5] RA Tinguely *et al* (2021) Nucl. Fusion **61** 26003-26017
[6] RA Tinguely *et al* (2021) Submitted to Nucl. Fusion.
[7] A Fasoli *et al* (2000) Phys. Lett. A **265** 288-293
[8] D Testa *et al* (2012) Nucl. Fusion **52** 094006
[9] A Fasoli *et al* (2002) Plasma Phys. Control. Fusion **44** B159
[10] D Testa *et al* (2015) Nucl. Fusion **55** 123010
[11] P Puglia *et al* (2021) In progress.
[12] RJ Dumont *et al* (2018) Nucl. Fusion **58** 8 082005
[13] M Fitzgerald *et al* (2021) In progress.