

## A stability study of $\alpha$ -particle driven Alfvén eigenmodes in JET D-T plasmas

J. Ferreira<sup>1</sup>, D. Borba<sup>1</sup>, R. Coelho<sup>1</sup>, L. Fazendeiro<sup>1</sup>, A.C.A. Figueiredo<sup>1</sup>,  
N. F. Loureiro<sup>1</sup>, F. Nabais<sup>1</sup>, P. Rodrigues<sup>1</sup>, J. Conboy<sup>2</sup>, M. Fitzgerald<sup>2</sup>,  
S.E. Sharapov<sup>2</sup>, I. Voitsekhovitch<sup>3</sup>, and JET Contributors<sup>§</sup>

*EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK*

*<sup>1</sup>Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico,  
Universidade de Lisboa, 1049-001 Lisboa, Portugal*

*<sup>2</sup>CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*

*<sup>3</sup>EuroFusion Consortium Programme Unit, Boltzmannstr. 2, D-85748, Garching, Germany*

### Abstract

As a contribution to the effort towards the assessment of future scenarios with tritium and deuterium-tritium (D-T) mixture plasmas in the Joint European Torus (JET), a scientific workflow that has recently been developed for the systematic linear-stability assessment of Alfvén eigenmodes in the presence of fusion born  $\alpha$ -particles, is here applied to a representative JET D-T scenario.

### Introduction

Fusion-born  $\alpha$ -particles are ubiquitous in D-T burning plasmas as they comprise a considerable part of the total heating energy. Although being in minority they are born with high energies  $\sim 3.5$  MeV for a deuterium-tritium reaction, and being thus super-Alfvénic they can potentially destabilize global MHD modes such as the Alfvén eigenmodes (AEs). In some conditions these instabilities can strongly enhance the radial transport of this energetic population with serious consequences on burning performance and wall damage [Sharapov]. These are crucial problems, especially for future machines like ITER or DEMO, and a good understanding of the energetic particle physics supported by validated modelling tools is therefore of particular importance in order to better predict and plan burning plasma scenarios.

Many experiments and theoretical studies done during the last 20 years have improved our knowledge, pushed the development of better diagnostic techniques, and allowed the opportunity to enhance our numerical tools. Notwithstanding these great efforts further studies can be done, specially taking advantage of the forthcoming JET D-T campaign, to extend our understanding of energetic particle-wave interaction physics in plasmas surrounded by metallic walls. The

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<sup>§</sup>See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

preparation of the next DT campaign is therefore of crucial importance and motivates the work here presented. As a contribution to the assessment of future DT scenarios, a scientific workflow that has recently been developed for the systematic linear-stability assessment of Alfvén eigenmodes (AE) in the presence of fusion born  $\alpha$ -particles is here used to analyze a representative JET DT scenario.

### Linear stability analysis of Alfvén eigenmodes

In this work we follow a similar procedure that has been used to assess the stability of AEs in ITER burning-plasma scenarios [Rodrigues 2014, 2015; Figueiredo 2015]. As outlined in Figure 1, from an equilibrium picked from a TRANSP [Goldston 1981] run of a typical JET D-T discharge, which is then refined by CHEASE [Luetjens 1996] and/or HELENA [Huysmans 1991] equilibrium codes, all possible AEs are systematically searched using the ideal-MHD code MISHKA [Mikhailovskii

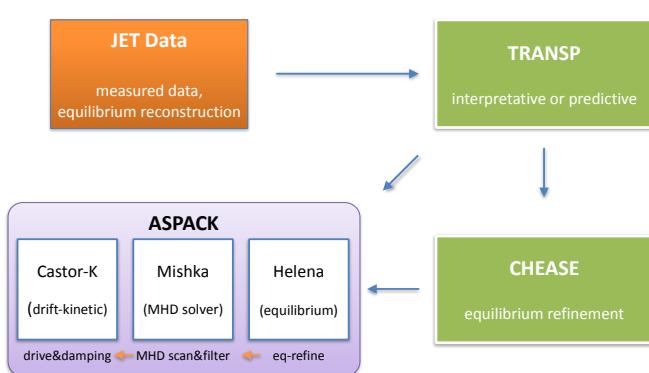


Figure 1 - Diagram of the workflow followed in the present study for the AE linear-stability assessment by the  $\alpha$ -drive.

modes are then analysed. Also of significant importance are the radiative damping, continuum damping and collisional AE damping, which are not taking into account here but will be part of a future publication. Also, the mechanisms responsible for wave damping on the impurities and He ash populations are neglected in the present study owing to the fact that is reasonable to assume that they are low when compared with the ion and electron damping

1999] by intensively scanning over a frequency and wave-number range. The linear stability of these modes is then evaluated by computing the energy exchange between these AEs and the fusion as, thermal D, T and electron populations, using the drift-kinetic code CASTOR-K

[Borba 1999; Nabais 2015]. The  $\alpha$ -particle drive and background damping of these

### Results and Discussion

A high-performance fusion JET D-D experimental pulse was selected for this study and is used as a reference for a predictive TRANSP analysis to extrapolate that discharge to a mixed D-T plasma scenario, and therefore estimate the  $\alpha$  content that could be reached in future JET D-T experiments. Relevant operational parameters for the selected discharge are: toroidal magnetic field of  $B_T = 3.46$  T at the magnetic axis, plasma current of  $I_{\text{plasma}} = 3\text{MA}$ , central ion and electron temperatures of  $T_{i0} \sim 20$  keV and  $T_{e0} \sim 7$  keV, and a D-T mixture of the order 60%/40% at the

plasma core. From this run a time slice is chosen during the burning phase for the systematic linear assessment of the AEs. This is illustrated in figure 2 where ion and electron temperature and density profiles, together with the  $\alpha$  content expressed by the  $\beta_\alpha$  normalized pressure and radial derivative profiles, as well as the safety factor and ion mass profiles are shown for  $t = 46.38$ s, around the time  $\alpha$  particles start to destabilize AEs. A dynamical study to evaluate the impact of current diffusion (evolution of safety-factor profile) and the increase of  $\alpha$  content on the stability of AEs along the discharge is left as future work.

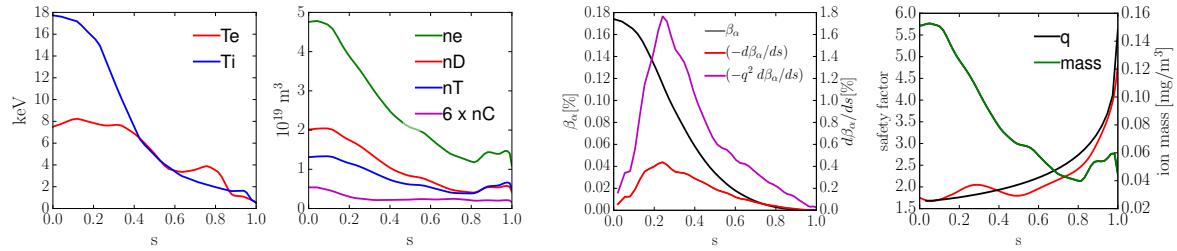


Figure 2 – Plasma profiles taken at  $t=46.38$ s from the TRANSP extrapolation to DT of a JET DD pulse #40214. From left to right, figure shows ion and electron temperature profiles, density profiles for different species, normalized  $\alpha$ -pressure ( $\beta_\alpha$ ) and radial derivatives, ion mass and safety-factor profiles (from TRANSP in red, EFIT reconstruction from DD in black), as function of “ $s$ ”, the square root of the normalized poloidal flux.

As illustrated in the rightmost plot of figure 2, the safety-factor ( $q$ ) profile for the reconstructed equilibrium by EFIT (in black) for the reference DD pulse is monotonic, contrary to the self-consistently equilibrium calculated by TRANSP where current diffusion is solved. Without loss of generality we have chosen to use the simpler monotonic- $q$  equilibrium for this preliminary analysis. The non-monotonic self-consistent TRANSP equilibrium will be assessed in future work. As described earlier, for the selected equilibrium a set of allowed AEs is systematically found and each mode is then processed by CASTOR-K to calculate the drive due to interaction with  $\alpha$ -particles

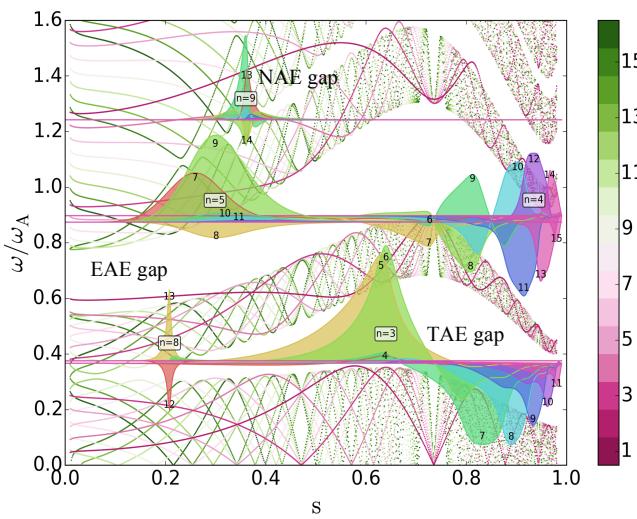


Figure 3 - ideal MHD continuum spectra for  $n$  up to 16, as function of square root of the normalized poloidal flux ( $s$ ). AE modes are shown within the TAE, EAE and NAE gaps.

and wave damping on the thermal D ions, T ions and electrons. The total effective normalized growth rate is then given by  $\gamma/\omega = (\gamma_\alpha + \gamma_D + \gamma_T + \gamma_e)/\omega$ , where  $\gamma_s$  is the AE growth rate for the interaction with the population “ $s$ ”, and  $\omega$  the angular AE frequency. Positive growth rates quantify an energy transfer to the wave (drive), whereas negative values are related with wave damping. In figure 3 we show the ideal MHD continuum spectra for the aforementioned equilibrium, and

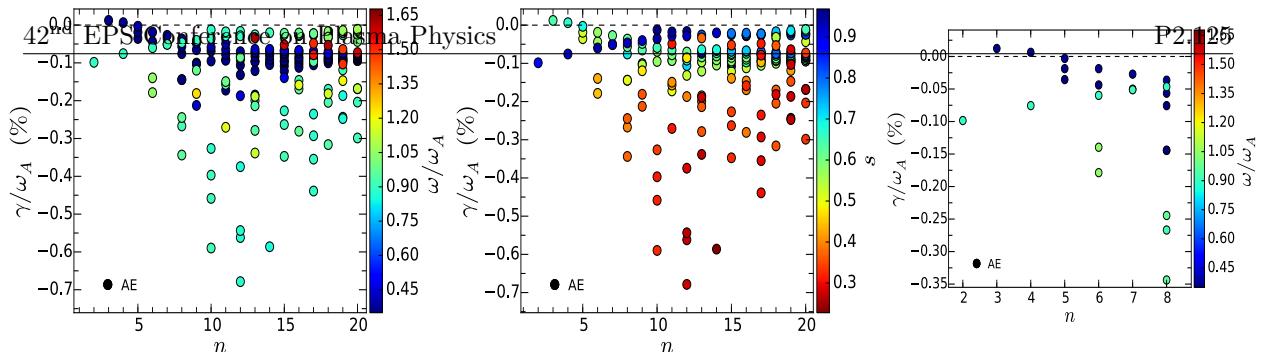


Figure 4 – Total growth rates for all the AEs found for  $n$  up to 20. From left to right, the first plot shows that the most unstable modes are low- $n$  TAEs, but many of the high- $n$  EAEs ( $\omega/\omega_a \sim 1$ ) that are found close to the marginal stability threshold can start to have a deleterious role with the increase of  $\beta_a$ . In the middle plot each mode is colored by the radial location of its peak amplitude. A careful analysis shows that modes closer to the unstable threshold are localized in the outer half of the plasma, where the ion damping is significantly lower than in the very hot inner core. Lastly, in the rightmost plot, we plot the low- $n$  AEs in the region of interest, where the only unstable modes were found.

the structure and localization of some of the AEs that can be found within the gaps. The stability threshold for each mode (more than 400 AE where found) is determined by balancing the energetic ion drive against the dominant damping mechanisms. In figure 4 we show the total growth rates for all AEs found. A comprehensive analysis of these results will be left for a future publication. As a summary of this preliminary assessment we found that the outer radial low- $n$  TAEs, localized in a lower ion-damping region, are more easily destabilized in spite of being driven by fewer  $\alpha$ -particles. The high ion Landau damping in the very hot inner half of the plasma may overcome the  $\alpha$ -drive. Future work will try to assess if core localized AEs can be destabilized in JET D-T hot-ion plasmas.

### Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the IST, FCT, CCFE, or the European Commission. IST activities received financial support from “Fundação para a Ciência e Tecnologia” (FCT) through project UID/FIS/50010/2013. All computations were carried out using the HELIOS supercomputer system at the Computational Simulation Centre of the International Fusion Energy Research Centre (IFERC-CSC) in Aomori, Japan, under the Broader Approach collaboration between Euratom and Japan implemented by Fusion for Energy and JAEA. PR was supported by EUROfusion Consortium grant no. WP14-FRF-IST/Rodrigues and NFL was supported by FCT grant no. IF/00530/2013.

### References

- [Borba 1999] D. Borba and W. Kerner, J. Comput. Phys. 153 (1999) 101. [Figueiredo 2015] A. C. A. Figueiredo *et al.* “Comprehensive evaluation of the linear stability of Alfvén eigenmodes driven by alpha particles in an ITER baseline scenario”, to be submitted to Nucl. Fusion (2015), also see this conference P4.123. [Goldston 1981] R. J. Goldston, D. C. McCune, *et al.*, J. Comput. Phys. 43, (1981) p. 61. [Horton 2015] L. Horton and JET Contributors, 12th International Symposium on Fusion Nuclear Technology, ICC JEJU, Jejun Island Korea, oral presentation (2015). [Huysmans 1991] G. Huysmans *et al.*, Int. J. Mod. Phys. C 2 (1991) 371. [Luetjens 1996] H. Luetjens, A. Bondeson, O. Sauter, Comput. Phys. Commun. 97 (1996) 219 [Mikhailovskii 1999] A.B. Mikhailovskii *et al.*, Plasma Phys. Rep. 23, (1997), p. 844. [Nabais 2015] F. Nabais *et al.*, Plasma Sci. Technol. 17 (2015), p. 89. [Rodrigues 2014] P. Rodrigues *et al.*, Proceedings of the 25th IAEA Fusion Energy Conference, Saint Petersburg, Russia, TH/P3-25 (2014), arXiv:1410.2744. [Rodrigues 2015] P. Rodrigues *et al.*, “Systematic linear-stability assessment of Alfvén eigenmodes in the presence of fusion  $\alpha$ -particles for ITER-like equilibria”, accepted by Nucl. Fusion (2015), also see this conference P4.124. [Sharapov 2011] S.E. Sharapov, I. Voitsekhovitch, *et al.*, 38th EPS on Plasma Physics, Strasbourg, France, P5.117, (2011). [Sharapov 2012] S.E. Sharapov, *et al.*, IAEA, San Diego, United States of America, OV/4-3, (2012). [Sharapov 2013] S. E. Sharapov *et al.*, Nucl. Fusion 53 (2013) 104022