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A Stability Study of α-Particle Driven Alfvén Eigenmodes in JET D-T Plasmas

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A stability study of α-particle driven Alfvén eigenmodes in JET D-T plasmas

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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 α-particles, is here applied to a representative JET D-T scenario.

Introduction

Fusion-born α-particles are ubiquitous in burning plasmas as they comprise a considerable part of the total heating energy. Although being in minority they are born with high energies ~3.5 MeV for a deuterium-tritium reaction (D-T), and thus being super-Alfvénic they can potentially destabilize global MHD modes such as the Alfvén eigemodes (AEs). In some conditions these instabilities can strongly enhanced 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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[§]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 α-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 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 αs, thermal D, T and electron populations, using the drift-kinetic code CASTOR-K [Borba 1999; Nabais 2015]. The α-particle drive and background damping of these 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

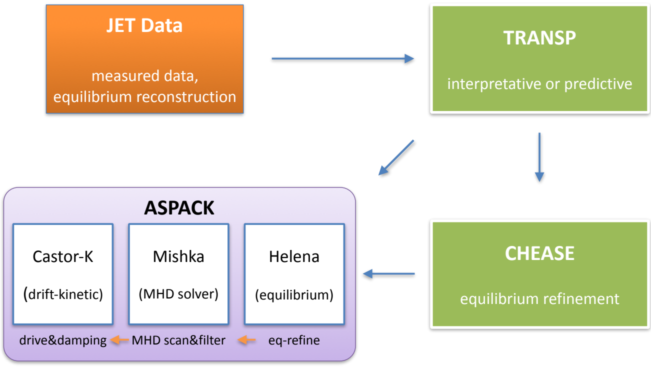

Figure 1 - Diagram of the workflow followed in the present study for the AE linear-stability assessment by the α-drive.

Results and Discussion

A high fusion performance JET D-D 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 α content that could be reached in future JET 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 $I_{plasma} = 3$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 timeslice is chosen 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 α content expressed by the β_α normalized pressure and radial derivative profiles, as well as the safety factor and ion mass profiles are shown for t=46.38s. A dynamical study to evaluate the impact of current diffusion (evolution of safety-factor profile) and the increase of α content on the stability of AEs along the discharge is left as future work.

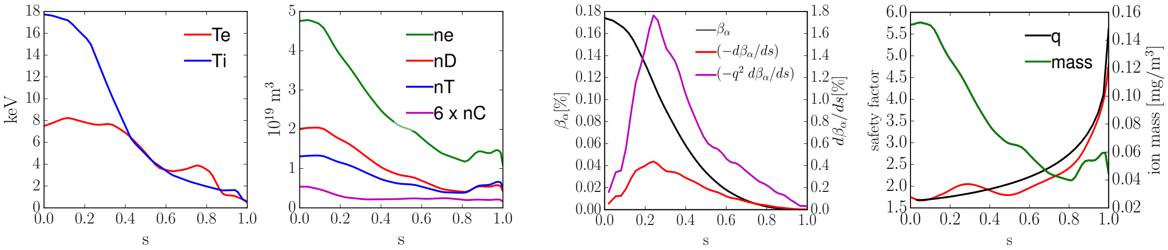

Figure 2 – Plasma profiles taken at t=46.38s from the TRANSP extrapolation to DT of a JET DD pulse #40214. From left to right, figure shows ion and electron temperature profiles, density profiles for different species, normalized α-pressure (βα) and radial derivatives, ion mass and safety-factor profiles (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 α-particles 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 γ_s is the AE growth rate for the interaction with the population "s", and ω 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 the structure and localization of some of the

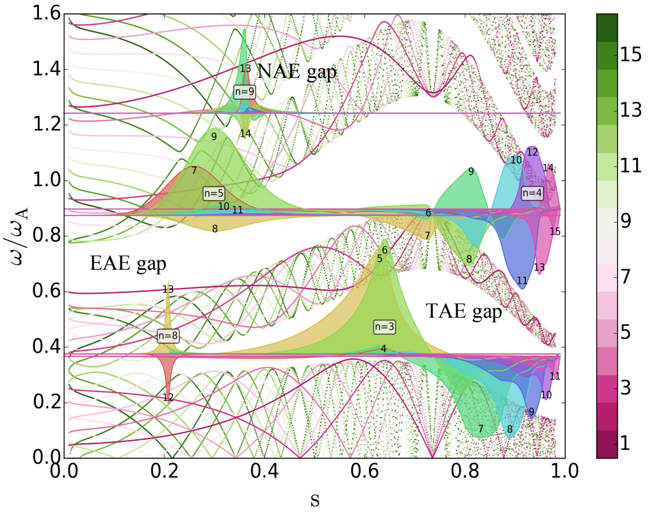

Figure 3 - ideal MHD continuum spectra for n up to 16, as function of square root of the normalized poloidal flux (s). AE modes are shown within the TAE, EAE and NAE gaps.

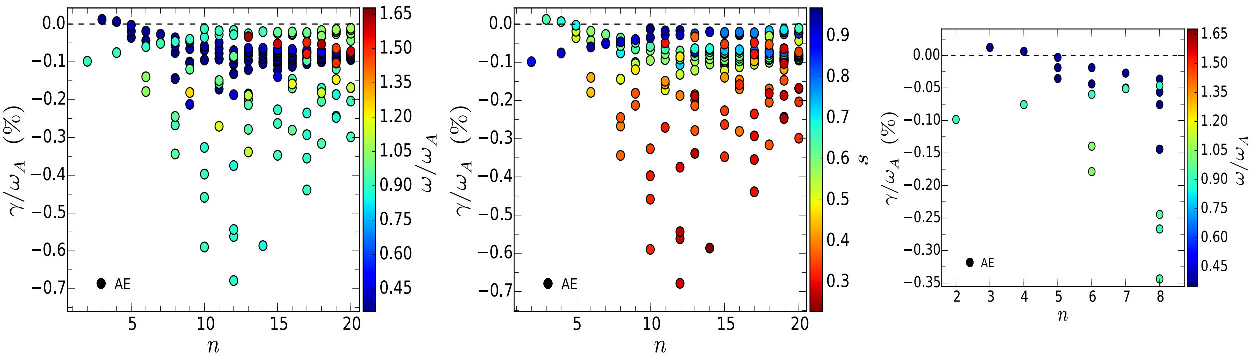

Figure 4 – Total growth rates for all the AEs found for n up to 20. From left to right, the first plot shows that the most unstable modes are low-n TAEs, but many of the high-n EAEs (ω/ω_α~1) that are found close to the marginal stability threshold can also have a deleterious role. In the middle plot 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.

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 α-particles. The high ion Landau damping in the very hot inner half of the plasma may overcome the α-drive. Future work will try to assess if core localized AEs can be destabilized in JET D-T hot-ion plasmas.

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