Linear stability of α-particle–driven Alfvén Eigenmodes in ITER burning-plasma scenarios

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Plasma heating during the burning regime in tokamaks will rely upon the energy of fusion-born α-particles which must be kept confined to keep the plasma hot and prevent wall damage. However, such particles can drive Alfvén Eigenmodes (AEs) unstable and can thus be transported away from the burning core. Before experiments on ITER are performed we rely upon extrapolation from present machines and simple predictive models to determine which AEs will interact most with fusion α's for a given scenario. On the other hand, *ab initio* simulations able to provide a self-consistent solution of the interaction between α-particles and the bulk plasma are still computationally expensive for routine use in experiment design and planning. Therefore, more efficient approaches must be devised so that large swaths of parameter space can be explored, identifying the most unstable cases for later analysis with more specialized tools.

In this work an approach is presented that systematically evaluates the linear stability of all possible AEs for a given equilibrium [1]: these are found by intensively scanning over a frequency and wave-number range with the ideal-MHD code `MISHKA` [2], while the energy transfer between them and the plasma species (fusion α's, DT fuel, electrons and He ash) is evaluated with the drift-kinetic code `CASTOR-K` [3, 4]. The computational efficiency of the `MISHKA/CASTOR-K` pair is the key to handle the very large number of AEs involved in systematic stability assessments. The ability to produce a list of possible AEs ranked by their linear growth rate is illustrated with an ITER baseline scenario [5, 6]. Small variations of the safety factor q are then considered, which result from slightly changing the plasma current. We shall find that such small changes can have a large influence on the linear-stability properties of AEs for this ITER baseline scenario.

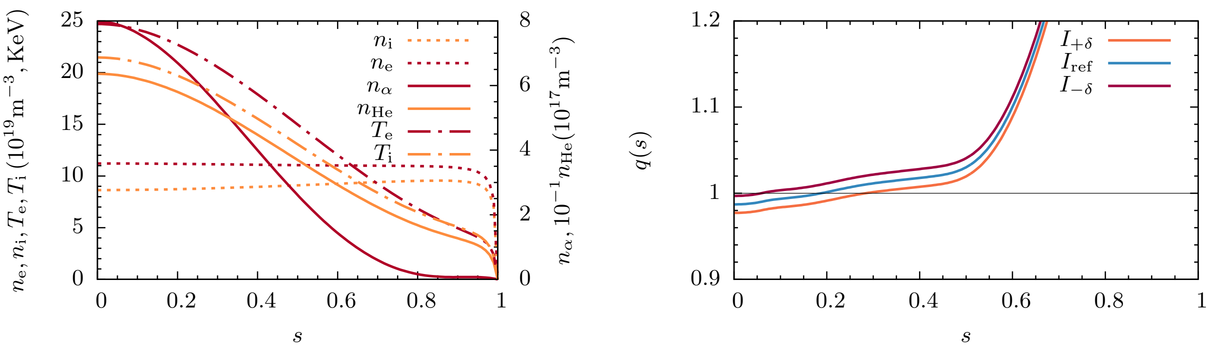

Figure 1: Kinetic (left) and safety-factor profiles (right) corresponding to three values of I_p.

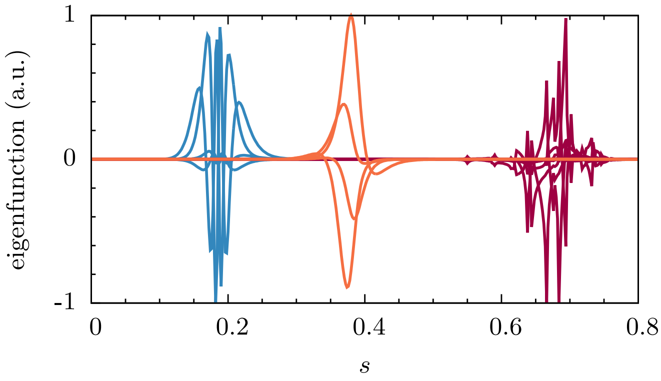

Figure 2: Examples of AEs with grid index $h_g = 0.005$ (well resolved, centre), 0.3 (marginally resolved, left), and 0.95 (poorly resolved, right).

Figure 1 displays the kinetic profiles of the aforementioned ITER scenario, with $I_p = 15\,\mathrm{MA}$, on-axis magnetic field $B_0 = 5.3\,\mathrm{T}$, minor radius $a = 2\,\mathrm{m}$, and magnetic axis at $R_0 = 6.4\,\mathrm{m}$. The DT fuel mix ratio is $n_D/n_T = 1$ and their combined density is $n_i = n_D + n_T$. The q profile is also plotted in Figure 1, with $q(0) = 0.987$. In both plots, $s^2 = \psi/\psi_b$, ψ is the poloidal flux, and ψ_b is its value at the boundary. Two other profiles correspond to small variations of the reference value ($I_{ref} = 15\,\mathrm{MA}$) for I_p and shall be discussed latter.

The linear-stability assessment starts with an equilibrium computed by `HELENA` [7], using the kinetic profiles and the I_p value, which is then employed by `MISHKA` to find the frequency and radial structure of all AEs for a toroidal number n in the range $1 \leqslant n \leqslant 50$ and poloidal harmonics $n-1 \leqslant m \leqslant n+15$. The upper limit for n is set by $k_\perp \rho_\alpha \lesssim 1$, whence $n \lesssim (s/q)/(\rho_\alpha/a) \approx 50$, with $\rho_\alpha/a \approx 1/100$ the normalized α-particle gyro-radius, $k_\perp \approx nq/(as)$, $q \approx 1$, and $s \approx 0.5$. For each n, the frequency range $0 \leqslant \omega/\omega_A \leqslant 1$ [where $\omega_A = V_A(0)/R_0$ and $V_A(0)$ is the on-axis Alfvén velocity] is sampled in small steps of size 2×10^{-5} and each sample becomes `MISHKA`'s initial guess. If the resulting AE solution does not converge in 5 iterations, it is discarded and the next sample is tried. Converged AEs are next filtered to remove spurious solutions with radial wavelengths shorter than the radial mesh size. AEs with sharp variations display a large grid index h_g while a lesser one corresponds to smaller discretization errors [1], as illustrated in Figure 2. Only AEs with $h_g \leqslant 0.3$ are considered. AEs matching the Alfvén continuum at radial positions where their amplitude exceeds $\frac{1}{100}$ of its maximum value are also discarded. Next, `CASTOR-K` evaluates the energy exchange δW_j between every selected AE and each species j: the α-particles described by a radius-independent slowing-down energy distribution (with crossover energy $E_c = 730\,\mathrm{KeV}$ and dispersion $\Delta_E = 50\,\mathrm{KeV}$ around the birth energy) and then three thermal species (DT ions, electrons, and He ash), all described by local Maxwellians [1].

Although other sources of energetic particles are foreseen for the ITER scenario concerned (e.g., 40 MW of combined NBI and ECRH power) [6], only fusion-born α-particles are considered in this work. Radiative-damping evaluation is computationally costly and performed only for the most unstable ones [1], but here it will be left to future work. So, the net linear growth rate is $\gamma = \gamma_\alpha + \gamma_{DT} + \gamma_e + \gamma_{He}$, with $\gamma_j = \mathrm{Im}(\delta W_j)/(2\omega W_k)$ and W_k the AE's kinetic energy [3].

Three different magnetic equilibria are next considered, with I_p assuming the reference value $I_{ref} = 15\,\mathrm{MA}$ and then two small perturbations of the latter, respectively $I_{+\delta}$ and $I_{-\delta}$, where $\delta = 0.16\,\mathrm{MA}$. The linear-stability assessment of these three cases is summarized in Figure 3,

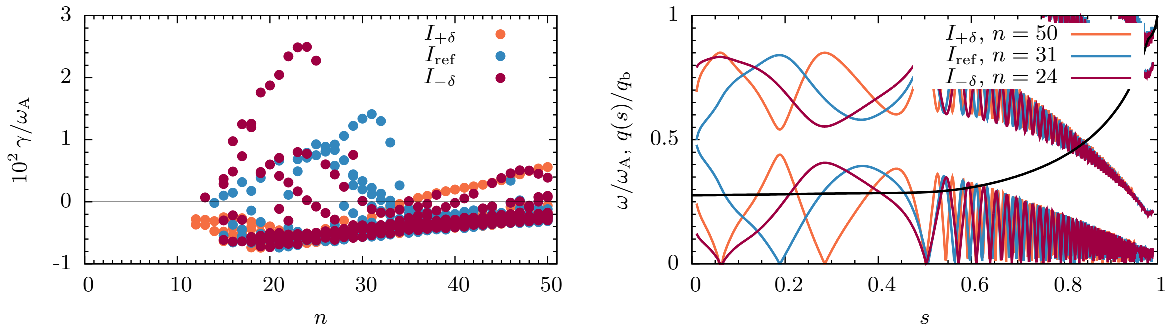

Figure 3: Linear growth rate versus n (left), Alfvén continuum corresponding to the most unstable n (right), and q profile for $I_p = I_{ref}$ normalized to its boundary value $q_b = 3.57$.

where only Toroidicity-induced AEs (TAEs) are shown for clarity. The reference case has its most unstable AEs around $n \approx 31$, corresponding to highly localized low-shear TAEs (LSTAEs) within the region $s \lesssim 0.5$, where the large radial separation between frequency gaps allows them to be excited. Actually, the most unstable AEs arises in the frequency gap located at $s \approx 0.37$ and depicted in Figure 3. Non-localized AEs coupling different frequency gaps only show in the plasma outer half, where the shear is higher and the frequency-gap separation is smaller. However, because the TAE gap closes towards the edge, most non-localized AEs forcibly interact with the Alfvén continuum and are assumed to be completely damped [1]. Changing I_p by the small amount $\pm\delta$, whilst keeping the same kinetic profiles, results in new magnetic equilibria whose q profiles are depicted in Figure 1 and for which $q(0)$ changes by $\pm 1\%$ of the reference value. The consequences are noticeable: The toroidal mode number n of the most unstable AEs drops by 20% whilst the linear growth rate almost doubles for the lower current $I_{-\delta}$ [and thus higher $q(0)$]; Conversely, for the higher current value $I_{+\delta}$ [corresponding to lower $q(0)$], the majority of AEs become stabilized except some large-n AEs ($n \gtrsim 35$). These proceed from the second frequency gap located near $s \approx 0.45$ (Figure 3) and have their linear growth rate reduced roughly by half with respect to the reference case. For all these three I_p values, the most unstable modes are always even LSTAEs whose dominant poloidal harmonics are $m = n$ and $m = n+1$, so that their resonant surface has a radial location established by $q_{n,n} = 1 + 1/(2n)$.

The plots in Figure 4 are useful to bring some insight into these results. They clearly indicate that lowering I_p also moves the radial position of the most unstable AEs inwards, and vice versa. The relation between the AEs location and I_p is better understood if the latter is replaced by the on-axis value $q_0 \equiv q(0)$ and the safety factor is approximated by $q(s) = q_0 + \sigma s$ in the low-shear region, whence $\sigma s = 1 - q_0 + 1/(2n)$. Recalling that for efficient energy transfer the most unstable AEs follow $k_\perp \Delta_{orb} \sim 1$, with $\Delta_{orb} \sim aq/(\varepsilon\tilde{\Omega})$ the α-particle orbit width, $\tilde{\Omega}$ its gyrofrequency normalized to ω_A, and $\varepsilon = a/R_0$, one finds $n + (1-2\zeta)/(4n) + 1 = \zeta(1-q_0)$, where $\zeta \equiv \varepsilon\tilde{\Omega}/\sigma = (q/\sigma)(\Delta_{orb}/a)^{-1}$. Subtracting the former relation and its evaluation with the values n_{ref} and q_{ref}, which correspond to the reference case, gives

$$\left(1 + \frac{2\zeta - 1}{4 n_{ref}\, n}\right)(n - n_{ref}) = -\zeta\,(q_0 - q_{ref}). \qquad (1)$$

ITER parameters are $\sigma \approx 0.07$, $\varepsilon \approx 0.3$, and $\tilde{\Omega} \approx 230$, whence $\zeta \approx 10^3$. Therefore, increasing q_0 above q_{ref} lowers n below n_{ref} and conversely, as observed in Figures 3 and 4. On the other hand, the rise of γ/ω_A as q_0 increases (or I_p drops) is due to the larger number of α-particles found as AEs move inwards within $0.2 \lesssim s \lesssim 0.6$, where dn_α/ds is almost constant.

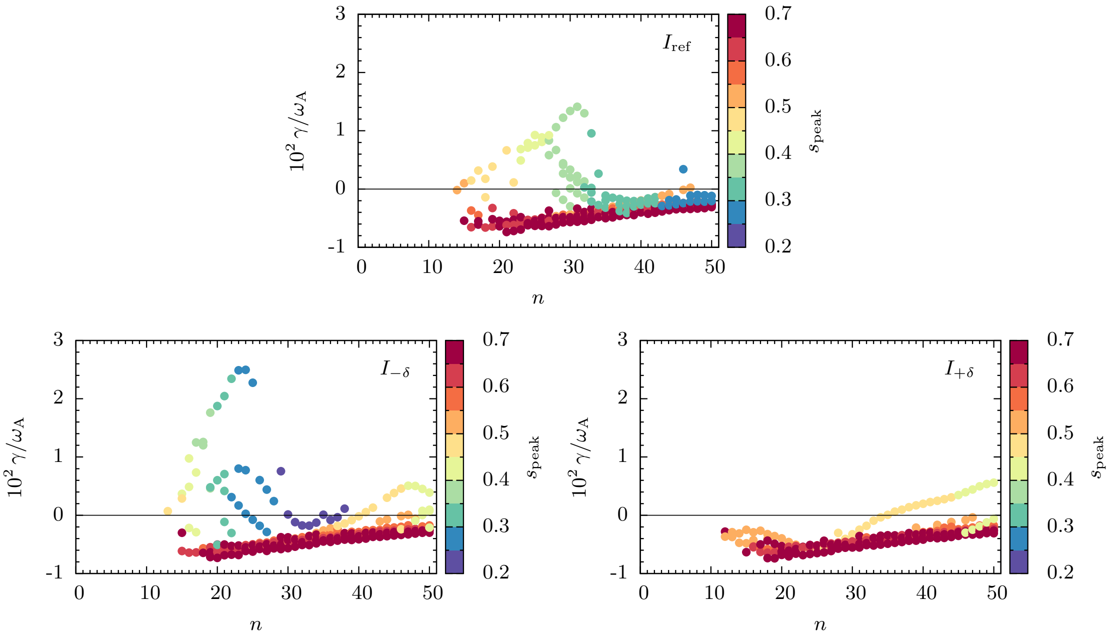

Figure 4: $\gamma/\omega_{\mathrm{A}}$ versus n, with each AE colored by the radial location of its peak amplitude.

In summary, a computationally efficient approach for systematically assessing the linear stability of α-driven AEs has been developed and used with an ITER baseline scenario. Predicted values for $\gamma/\omega_{\mathrm{A}}$ and n of the most linearly unstable AEs were found to be highly sensitive to small changes in I_{p} (or q_0). Moreover, this sensitivity was shown to proceed from the large value attained by ζ in Eq. (1) due to the very low magnetic shear in the plasma core, denoted by having $\sigma \ll 1$, and very large gyrofrequency $\tilde{\Omega} \gg 1$.

Acknowledgments

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