

Alfvénic Instabilities Driven by Alpha Particles in ITER Scenarios

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Abstract. The stability of proposed ITER scenarios with respect to Alfvénic instabilities driven by fusion-produced alpha particles is investigated by hybrid MHD-particle simulations. Three cases are considered: the monotonic safety-factor scenario (SC2), the reversed-shear one (SC4) and a flat safety-factor profile “hybrid” scenario (SCH). Though all the cases are found unstable, growth rates are quite small. The effects of nonlinear mode dynamics on the alpha-particle confinement at the reference drive are negligible for the SC2 and the SCH cases. For the SC4 scenario, some broadening of the alpha-particle pressure profile is observed, indicating inconsistency problems of the scenario itself. Such problems could arise for the other scenarios as well in the presence of a stronger drive (e.g., because of a moderate increase in electron and bulk-ion temperatures, or the inclusion of energetic particles produced by additional heating methods). The SCH scenario, however, does not present relevant profile broadening, unless the threshold for Energetic Particle Mode (EPM) destabilization (a factor ~ 1.6 greater than the reference pressure gradient) is exceeded.

1. Introduction

The operation scenarios for next-step proposed burning-plasma experiments, such as ITER-FEAT [1, 2], are usually obtained from equilibrium and transport codes that do not account for the collective effects due to shear-Alfvén modes: the possibility that these modes are excited and, eventually, produce macroscopic transport of alpha particles themselves is neglected. Thus, consistency problems of the envisaged burning-plasma scenarios may occur, in particular with reference to the alpha-particle distribution radial profile and, therefore, to the fusion power density.

In this paper the stability of various ITER equilibria with respect to shear Alfvén waves is investigated by means of the Hybrid MHD-Gyrokinetic Code (HMGC); the plasma model adopted in this code has been described in Refs.[3, 4]. For simplicity we neglect the nonlinear mode-mode coupling among different toroidal mode numbers, then limiting the analysis to the evolution of a single toroidal mode n , while keeping fully nonlinear dynamics for energetic particles.

Three different ITER-FEAT scenarios have been considered: the reference monotonic- q scenario (SC2), the reversed shear scenario (SC4) and a recently proposed flat- q “hybrid” scenario (SCH). Here q is the safety factor. SC2 is an inductive, 15 MA scenario, with 400 MW fusion power and fusion yield $Q \simeq 10$. SC4 is a steady state, 9 MA, weak-negative shear scenario, with about 300 MW fusion power and $Q \simeq 5$; the q profile is characterized by $q_{min} \simeq 2.4$ and $r_{q_{min}}/a \simeq 0.68$ (with a being the minor radius of the torus). SCH is a steady state, 11.3 MA weak-positive shear scenario, with about 400 MW fusion power and $Q \simeq 5$. Data corresponding to the two former scenarios are available at the ITER Joint Work Site [6]; the SCH ones have been obtained by the package of simulation codes CRONOS [7]. Significant plasma and device parameters are reported in Table I, while the radial profiles of the relevant quantities are shown in Fig. 1. Note, in particular, the very different values of the local alpha-particle drive, $\alpha_H \equiv -R_0 q^2 \beta'_H$ (with R_0 being the major radius of the torus and β_H the ratio between alpha-particle and magnetic pressures, “prime” denoting the radial derivative). In order to have

a more complete picture of the Alfvén mode dynamics, we will extend our investigation to values of the on-axis β_H (β_{H0}) larger than the reference value ($\beta_{H0,\text{scenario}}$), while keeping the normalized profile, β_H/β_{H0} , unchanged.

TABLE I: Plasma and device parameters for the three considered ITER-FEAT scenarios. Here $q_{95\%}$ is the value of the safety factor at the surface where the poloidal flux is the 95% of the total, B_T is the on-axis toroidal magnetic field, n_{e0} , T_{e0} , n_{H0} and β_{H0} are the on-axis electron density, electron temperature, alpha-particle density and the ratio between alpha-particle and magnetic pressures, respectively, and $\alpha_{H,\text{max}}$ is the maximum value of the local alpha-particle drive, located at $r = r_{\text{max}}$.

	a (m)	R_0 (m)	$q_{95\%}$	B_T (T)	n_{e0} (10^{20}m^{-3})	T_{e0} (keV)	n_{H0} (10^{18}m^{-3})	β_{H0} (%)	$\alpha_{H,\text{max}}$	r_{max}/a
SC2	2.005	6.195	3.14	5.3	1.02	24.8	0.78	1.10	0.085	0.25
SC4	1.859	6.34	5.13	5.183	0.73	23.9	0.62	0.92	0.600	0.50
SCH	1.8017	6.3734	3.22	5.3	0.72	30.0	0.88	1.37	0.155	0.60

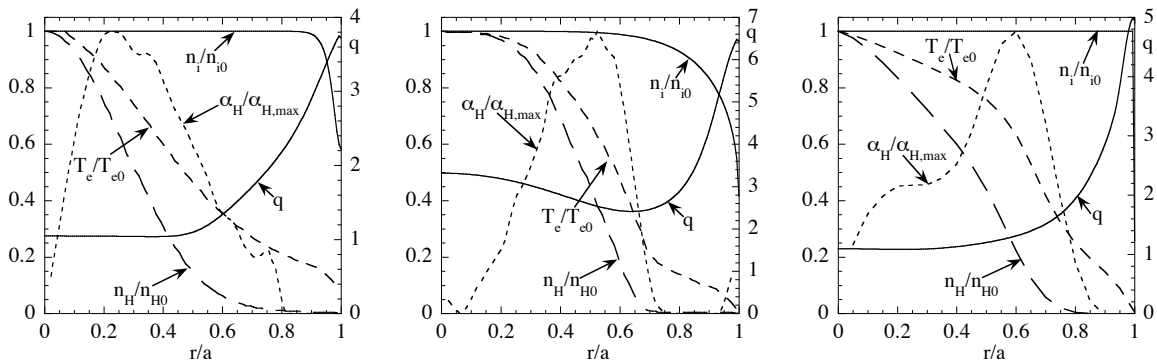


FIG. 1: Radial profiles of safety factor (q), normalized bulk-ion (n_i) and alpha-particle (n_H) densities, electron temperature (T_e), and alpha-particle local drive (α_H), for ITER-FEAT SC2 (left), SC4 (center) and SCH (right) scenarios.

2. Results

We first examine the linear dynamics of the considered ITER-FEAT scenarios, as it emerges from the first (low field amplitude) phase of the simulations. Figure 2 shows the growth rates obtained at different values of β_{H0} . Results for the three scenarios are reported: SC2 (left), SC4 (center) and SCH (right). It can be seen that all these cases are predicted to be unstable at the reference β_{H0} value, though with quite small growth rates. For all the scenarios, the most unstable modes correspond to low toroidal numbers ($n = 4$ in the SCH case, $n = 2$ in the other two cases). From Fig. 3 we see that these modes are localized in low-shear regions (the inner portion of the plasma for SC2 and SCH, mid radius for SC4), where they can easily avoid the damping interaction with the Alfvén continuum. A common feature of these modes is represented by their MHD-like nature: it can be shown that, in the limit of zero drive, they smoothly connect to MHD quasi-marginally-stable modes. The radial localization of the modes almost coincides with that of the maximum drive for SC2 and SC4, not for SCH. In the latter scenario, the mode grows around an inner flux surface with respect to the α_H peak. The fact that the mode can grow even though the drive is quite small is not surprising, because of its MHD nature (it exists even in the absence of energetic particles); at the same time, it justifies the very low growth rates obtained in this case.

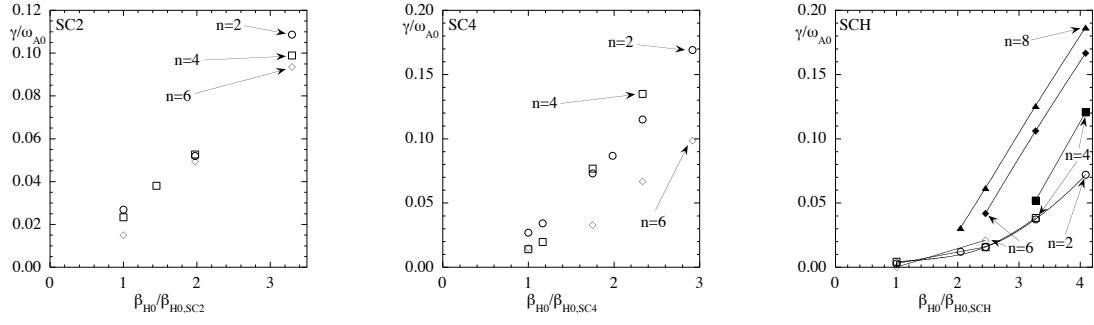


FIG. 2: Growth rate versus $\beta_{H0}/\beta_{H0,scenario}$ for three different ITER-FEAT scenarios: SC2 (left), SC4 (center), SCH (right). Modes with different toroidal numbers are considered.

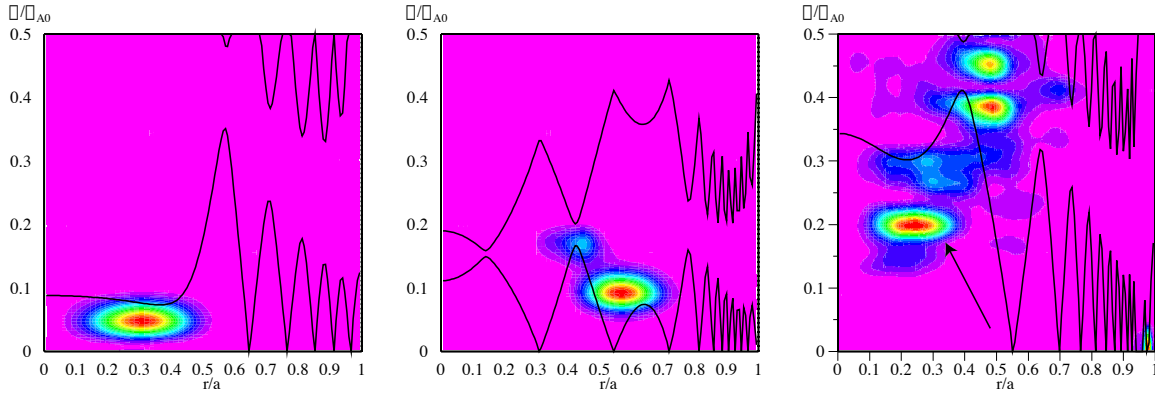


FIG. 3: Power spectra of scalar-potential fluctuations in the (r, ω) plane (with ω being the mode frequency), during the linear phase, for the SC2 $n = 2$ (left), SC4 $n = 2$ (center) and SCH $n = 4$ (right) cases with $\beta_{H0} = \beta_{H0,scenario}$. In the right frame an arrow indicates the dominant (though weak) mode. Upper and lower Alfvén continuous spectra are also plotted (solid line).

If the drive is artificially increased above that of the reference scenario (preserving its normalized radial profile), apart from the obvious increase of the growth rates of these MHD-like modes, we find that destabilization of fast-growing EPs can occur in the SCH case around the maximum drive radial position, as shown in Fig. 4 for the $n = 4$ case. At that position only heavily damped Alfvén oscillations can take place in the MHD limit. EPs appear only if the energetic-particle drive exceeds a certain threshold. In the SCH case, we find that this threshold corresponds to an alpha-particle energy content a factor ~ 1.6 greater than the reference value for $n = 8$ (note that, in the $n = 4$ case, considered in Fig. 4, the factor is ~ 2.6). This should not be considered unrealistically high, because at least two factors can cause an underestimation of the fast-ion energy density: first, the strong dependence of the fusion-produced alpha-particle density on the electron and bulk-ion temperatures, along with the intrinsic uncertainties of transport models (a 60% error in β_H can be accounted for by a 15% error in bulk-plasma temperatures); second, the fact that equilibrium profiles used in our simulations neglect the concurrent drive associated with the energetic particles produced by additional heating.

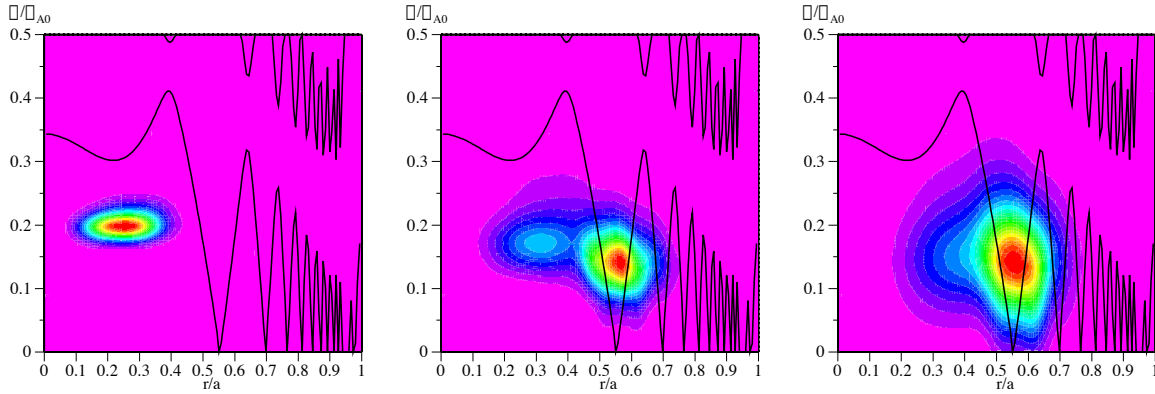


FIG. 4: Power spectra for the $n = 4$ modes, in the SCH scenario, at three different values of β_{H0} : $\beta_{H0} \simeq 2.5\beta_{H0,SCH}$ (below the EPM threshold; left), $\beta_{H0} \simeq 3.3\beta_{H0,SCH}$ (just above threshold; center) and $\beta_{H0} \simeq 4.1\beta_{H0,SCH}$ (well above threshold; right).

Concerning the destabilizing mechanisms, our simulations show that $n \lesssim 8$ EPMs are driven unstable mainly by the resonance with trapped energetic particles: indeed, they disappear if the mirroring term in the energetic-particle parallel dynamics is artificially removed. The MHD-like modes are apparently less sensitive to a specific resonance, and, consistently with their character, they do not discriminate between trapped and transit particle dynamics.

The investigation of the system nonlinear dynamics shows (Fig. 5 top) that the effects on the alpha-particle confinement at the reference drive values are very small for the SC2 and the SCH cases. For the SC4 scenario, some broadening of the alpha-particle pressure profile is observed, indicating a certain level of inconsistency of the scenario itself. Simulations performed with increased drive intensity show (Fig. 5 bottom) that a strong flattening of the alpha-particle pressure profile can occur in the inner plasma region for the SC2 case, while the global confinement of such particles is not significantly affected. The SC4 case presents more pronounced effects in the outer portion of the discharge, because of the outer localization of the modes, with less impact on the on-axis pressure value. Further diffusion due to saturated fields leads to particle losses even for relatively moderate drive increase. In the SCH scenario, no significant consequences are observed below the EPM threshold. If such threshold is exceeded, effects on the alpha-particle pressure are similar to those in the SC4 case, but more limited for given growth rate.

On the basis of these results, we can conclude that all the considered ITER scenarios deserve further investigations in order to assess their consistency with Alfvén mode dynamics. This is apparent for the SC4 case, which presents modifications of the alpha-particle pressure profile even at the reference fusion-alpha energy-density value. For the other two cases, the need for more accurate analyses is motivated by the difficulties in predicting exactly the energetic-particle energy content and, hence, in excluding that the system be characterized by significantly more unstable regimes. Note, however, that our model cannot address the dynamics of a plasma discharge on the long transport time scale. The stability of a given scenario is then analyzed by *assuming* the reference equilibrium, without considering how its formation is affected by the Alfvén mode dynamics itself. A multiple time-scale dynamic approach could then in principle show that the fast-mode dynamics is in fact regulated by the nonlinear effects

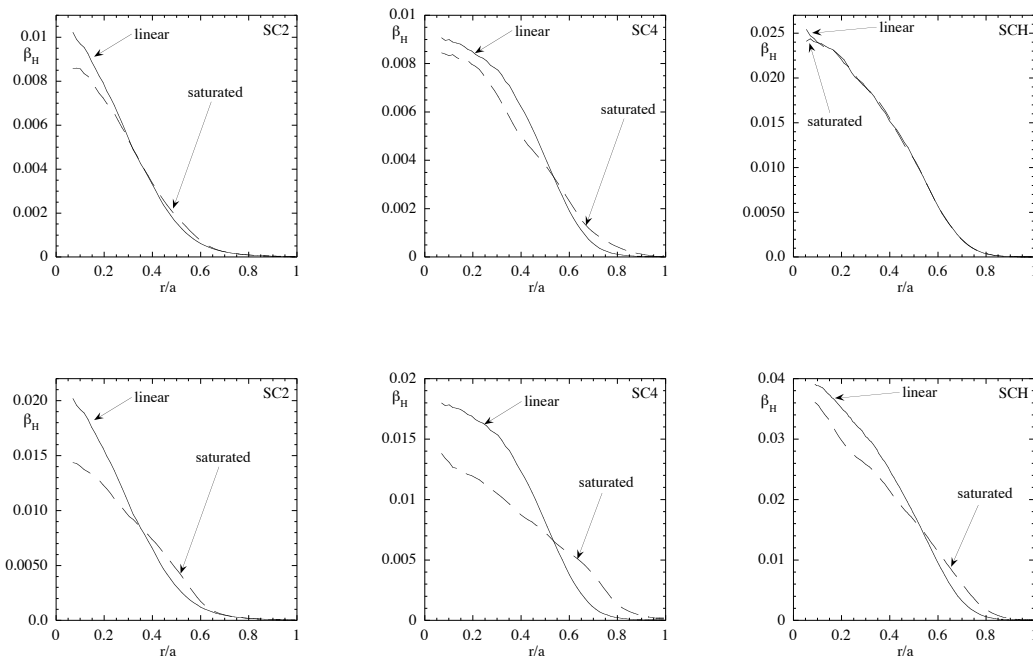


FIG. 5: Effects of the nonlinear mode saturation on the alpha-particle pressure profiles. In the top frames, the most unstable modes at the reference β_{H0} value have been considered, as in Fig. 3. The bottom frames refer to the most unstable modes found at increased drive intensity: namely, $n = 2$ for SC2 with $\beta_{H0} \simeq 2 \beta_{H0,SC2}$, $n = 2$ for SC4 with $\beta_{H0} \simeq 2 \beta_{H0,SC4}$, and $n = 8$ for SCH with $\beta_{H0} \simeq 3.3 \beta_{H0,SCH}$

produced by weaker Alfvén modes driven unstable while the alpha-particle pressure gradient is building up.

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