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Consistency of Proposed Burning Plasma Scenarios with Alpha Particle Transport Induced by Alfvénic Instabilities

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Particle simulations performed with the Hybrid MHD-Gyrokinetic simulation Code have shown [1] that transport and confinement properties of energetic ions in Tokamak plasmas can be significantly affected by shear Alfvén modes driven unstable by pressure gradients of the energetic ions themselves. In this paper, we investigate the consistency of envisaged scenarios for the three main burning-plasma proposed experiments (ITER-FEAT, IGNITOR and FIRE) with shear Alfvén mode dynamics and their effect on the energetic ion confinement.

Model simulations are performed retaining the relevant bulk-plasma parameters, the ion density n_i, the safety factor q profile and the normalized alpha-particle pressure profile (β_H/β_{H0}, with β_{H0} being the on-axis β_H value) of each scenario. The equilibrium magnetic configuration is instead approximated by assuming large aspect ratio ($R_0/a = 10$, with appropriate rescaling of β_{H0} in order to yield the desired value of $\alpha_H \equiv -R_0 q^2 \beta_H'$) and shifted circular magnetic surfaces. The effect of the Alfvén mode dynamics is examined by varying β_{H0}, while keeping the profile unchanged. We neglect, for simplicity, the nonlinear mode-mode coupling among different toroidal mode numbers, then limiting the analysis to the evolution of a single toroidal mode number, n, while keeping fully nonlinear gyrokinetic dynamics for energetic particles. We start considering the case of $n = 4$. Simulations refer to the case of an isotropic Maxwellian, instead of a slowing-down alpha-particle distribution function; the characterizing parameters of the alpha-particle population are rescaled, however, in such a way to reproduce wave-particle interactions, both with respect to the resonance frequency and the drive of the dominant Alfvén modes. In other words, we make the simulation (Maxwellian) distribution function approximately equivalent to the physical (slowing-down) one, as far as the wave-particle resonances are concerned. It can be shown that matching the dominant (slowing-down) energetic-particle resonance requires to fix the thermal velocity of the Maxwellian distribution as $v_{th,H} = 0.52(E_{\rm fus}/m_H)^{1/2}$, with $E_{\rm fus}$ being the birth energy of solwing-down particles and m_H their mass. For fusion alphas born at $E_{\rm fus} = 3.52$ MeV, $v_{th,H} = 1.59 \times 10^{-2} c$. Similarly, matching the drive intensity (and, as far as possible, the growth rate) requires $\alpha_{H,\rm Maxw} \simeq 1.68 \alpha_{H,SD}$, with the pedices representing the Maxwellian and the slowing-down distribution function, respectively. In the following, we will report the results in terms of the slowing-down-equivalent parameters.

Figure 1 shows the radial profiles of q, n_i/n_{i0}, β_H/β_{H0} and α_H/α_{H0} adopted in the simulations. For ITER-FEAT and IGNITOR, two different scenarios are considered: respective

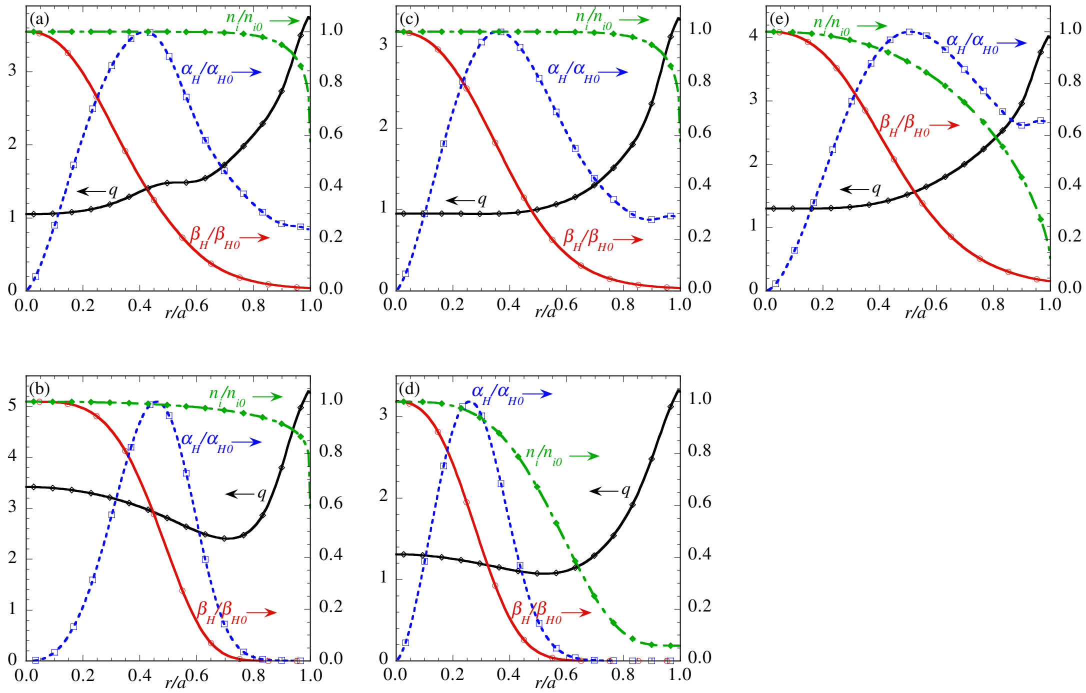

Figure 1: Radial profiles of q, n_i/n_{i0}, β_H/β_{H0} and α_H/α_{H0} adopted in the simulations: monotonic-q-profile equilibria are considered for ITER-FEAT (*a*), IGNITOR (*c*) and FIRE (*e*); reversed-shear profiles for ITER-FEAT (*b*) and IGNITOR (*d*).

monotonic-q-profile [5] scenarios are reported in Fig. 1 (*a*) and (*c*); the reversed-shear ones are shown in Fig. 1 (*b*) [6] and (*d*) [7]. A monotonic-q-profile FIRE scenario [5] is shown in Fig. 1 (*e*). In Fig. 2 (*left*) the growth rates of the dominant Alfvén modes are plotted versus $\beta_{H0}/\overline{\beta}_{H0}$, for the considered scenarios, with $\overline{\beta}_{H0}$ being the nominal on-axis β_H value for the respective scenario. Two facts emerge from our simulations: first, while the threshold for the destabilization of fast-growing Energetic Particle Modes [8] is generally quite (or very) far from the operation regimes, this is not the case for the reversed-shear ITER-FEAT scenario. Second, such modes are resonant in nature, and, if unstable enough, they saturate via an avalanche mechanism [1], which produces a macroscopic redistribution of the energetic-particle source. This can be seen from Fig. 2 (*right*), where the position of the radial surface that contains a fixed fraction (85%) of the alpha-particle energy is plotted versus $\beta_{H0}/\overline{\beta}_{H0}$ right after the avalanche phase.

These results indicates that for the reversed-shear ITER-FEAT scenario the constraints due to nonlinear energetic-particle dynamics could be very serious and should be taken into account to obtain a reference scenario consistent with the assumed fusion-product profile. This statement is strengthened by looking in greater detail at the nonlinear evolution of the mode-particle dynamics for such critical scenario. In the *top* frames, Fig. 3 shows the power spectra of the scalar-potential fluctuations in the $(r/a, \omega/\omega_{A,0})$ plane (with $\omega_{A,0} = v_{A,0}/R_0$, and $v_{A,0}$ being the on-axis Alfvén velocity); three times are considered: during the linear

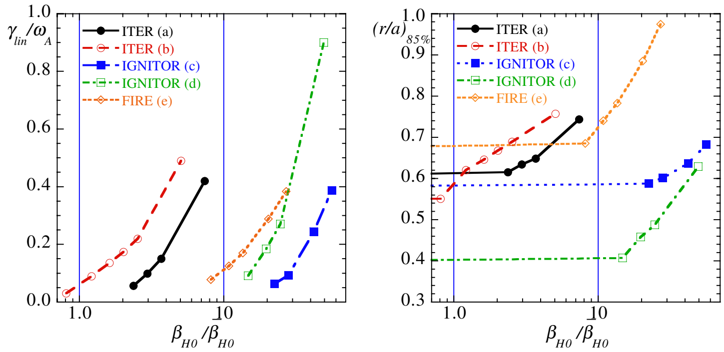

Figure 2: Growth rates (left) and radial positions of the surface containing 85% of the alpha-particle energy (right) versus $\beta_{H0}/\overline{\beta}_{H0}$, for the scenarios considered in Fig. 1.

growth of the mode (*left*), just after the avalanche phase (*center*), and in the fully saturated phase (*right*). The corresponding β_H profiles are plotted in the *bottom* frames. Results are shown for $\beta_{H0}/\overline{\beta}_{H0} \simeq 1.22$. It can be seen that, after the strong convective displacement (avalanche phase), a significant diffusion of energetic particles continues during the whole saturated phase because of the energetic-particle scattering in the saturated electromagnetic fields. This further effect is more pronunced for larger β_{H0} values (larger saturated field levels), as shown in Fig. 4, where the convective displacement data (the radial surface containing the 95% of the alpha-particle energy) are reported along with the residual saturated-phase diffusion time, τ_{diff}, normalized to the inverse Alfvén time.

Finally, we have checked the reliability of the main approximations adopted in these simulations: namely, large-aspect-ratio R_0/a and single toroidal mode number. In Fig. 5, the growth rates already reported in Fig. 2 (*left*) for the reversed-shear ITER-FEAT scenario are compared with those obtained for different values of n or R_0/a (with correspondingly rescaled β_{H0}). We see that the scaling of growth rates with R_0/a is satisfactory incorporated by the corresponding scaling of the drive intensity α_H (used to calculate the abscissa slowing-down-equivalent β_{H0} values). Regarding the dependence of the growth rates on the toroidal number, we observe that the modes with $n = 4$ are approximately as unstable as those with $n = 2$, and definitively more unstable than those with $n = 8$. We then expect that our conclusions should be qualitatively confirmed by a more detailed and complete investigation.

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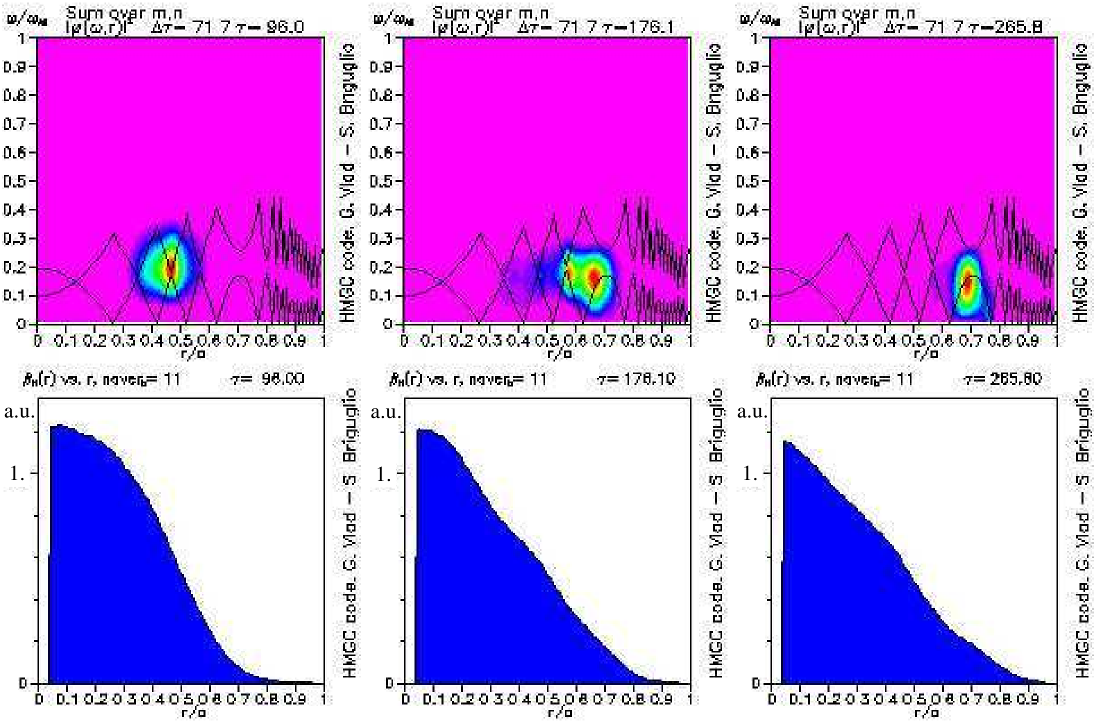

Figure 3: Power spectra of the scalar-potential fluctuations in the plane $r/a, \omega/\omega_{A,0}$ with the shear Alfvén continuous spectrum superimposed (*top*) and β_H profiles (*bottom*) for the reversed-shear ITER-FEAT scenario (but with $\beta_{H0}/\overline{\beta}_{H0} \simeq 1.22$), at three different stages: linear growth (*left*), just after the avalanche phase (*center*), fully saturated phase (*right*).

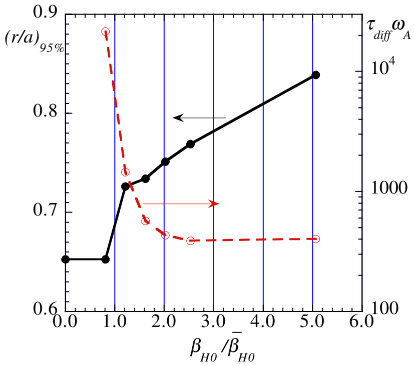

Figure 4: Radial position of the surface containing the 95% of the alpha-particle energy versus $\beta_{H0}/\overline{\beta}_{H0}$, for the reversed-shear ITER-FEAT scenario, along with the corresponding saturated-phase diffusion times.

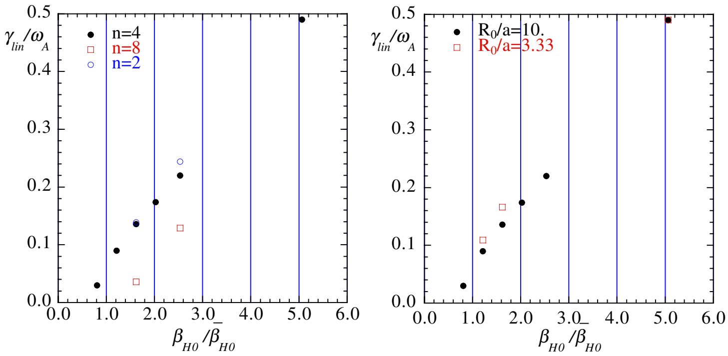

Figure 5: Growth rate for the case $n = 4$ and $R_0/a = 10$ versus $\beta_{H0}/\overline{\beta}_{H0}$, for the reversed-shear ITER-FEAT scenario, along with the growth rates obtained for different values of n or R_0/a.