Particle-in-cell investigation of the nonlinear saturation of Shear Alfvén Modes in hollow-q-profile tokamaks

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The stability and dynamics of Shear Alfvén modes in Tokamak equilibria characterized by non-monotonic q profiles is a relevant issue in the investigation of auxiliary-heated as well as ignited-plasma properties because of the role that such q profiles could play in obtaining improved confinement regimes. Two main elements could play a specific role in determining the Alfvén mode behaviour in these equilibria: first, the existence of an improved confinement region in an ignited plasma implies the formation of a steep thermal-plasma temperature profile, and, possibly, a much steeper alpha-particle radial distribution, with very high values of the energetic ("hot") ion pressure gradient, β_H'. Second, the particular shape of the q profile affects both the gap and the resonant-excitation frequencies, the radial extension and the toroidal coupling of the different poloidal harmonics as well as the energetic-ion drive intensity (estimated by $\alpha \equiv -R_0 q^2 \beta_H'$).

In this paper we want to address the latter point by analysing the results obtained by means of the Hybrid MHD-Gyrokinetic Code (HMGC) [1]. This code solves the set of reduced, $O(\epsilon^3)$ ($\epsilon \equiv a/R$), MHD equations for a low-β core plasma and the Vlasov equation for the energetic-ion population, using particle-in-cell techniques. Energetic particles contribute to the dynamic evolution of the electromagnetic fields through an energetic-ion pressure term in the MHD equations. The code, then, allows us to describe, in a self-consistent way, the resonant interaction between the Alfvénic modes and the energetic ions. Several approximations are however intrinsic to HMGC, such as large-aspect-ratio expansion, shifted circular magnetic surface equilibria and the assumption of an isotropic Maxwellian distribution function for the energetic ions. Much cautiousness has then to be used when comparing the simulation results with JET or other device's experimental ones. Moreover, in the specific numerical simulations presented here, we only retain full nonlinear wave-particle interactions, while neglecting nonlinear mode-mode couplings among different toroidal mode numbers n.

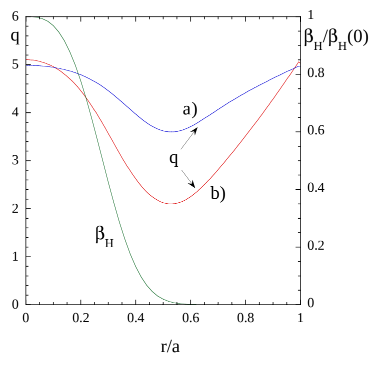

Fig. 1. The two different hollow q profiles and the β_H profile adopted in the simulation.

Figure 1 shows the β_H profile and two different hollow q profiles we consider in our simulations. All the simulations discussed in this paper refer to flat energetic-ion temperature profiles and consider the dynamics of $n = 4$ modes.

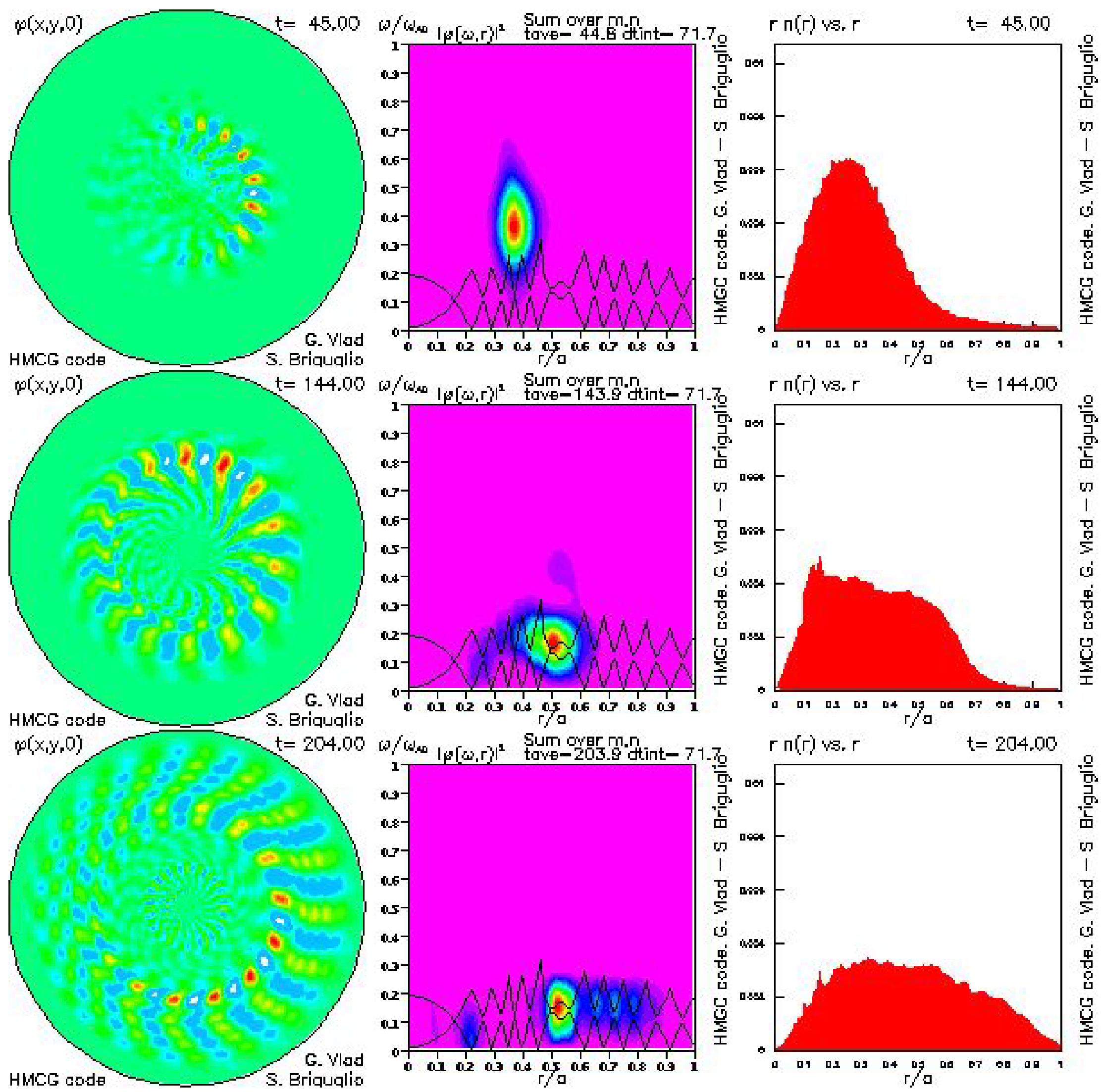

Fig. 2. Contour plot of the scalar potential ϕ at a fixed toroidal angle (left), power spectrum $\sum_m |\phi_{m,n}(r,\omega)|^2$ in the (r,ω) space (centre) and energetic-ion line density profile, $rn_H(r)$ (right), at three different times: linear growth phase (top), initial stage of nonlinear saturation (centre), fully saturated stage (bottom). The Alfvén continuum with the toroidicity induced gap is also drawn in the (r,ω) plot. Moderately hollow q profile, radially constant thermal-plasma density and $\beta_H(0) = 0.025$ have been assumed.

Figure 2 presents the results relative to the moderately hollow q profile (profile a in Fig. 1) and $\beta_H(0) = 0.025$. A radially constant thermal-plasma density is assumed. The contour plot of the scalar potential ϕ at a fixed toroidal angle, the power spectrum $\sum_m |\phi_{m,n}(r,\omega)|^2$ in the (r,ω) space and the energetic-ion line density profile, $rn_H(r)$, are shown at three different times: in the linear growth phase (top), during the initial stage of nonlinear saturation (centre), at a later, fully developed, saturated stage (bottom). The frequency gap is also drawn in the (r,ω) plot. We observe that an Energetic Particle Mode (EPM) [2], characterized by a real frequency deeply inside the continuum (top), is driven unstable by the resonant interaction with energetic ions. Its saturation takes place through a strong, convective, radial displacement of the energetic ions. The locally reduced drive is no longer able to overcome the strong continuum damping. The maximum of the power spectrum then migrates towards the gap (in order to minimize continuum damping) at outer radial positions, following the maximum β_H gradient (in order to maximize the drive). Once the gap is reached (centre), the mode assumes the most favourable localization and extension. In the present case, this corresponds to a localization around the zero-shear, minimum-q, surface.

This gap mode reaches its saturation by radially displacing energetic particles too. As the maximum β_H gradient propagates outwards, more and more poloidal harmonics are driven unstable with progressively outer localization. This “avalanche” process will stop as the displaced gradient becomes too weak to drive further poloidal harmonics unstable. The energetic ion density gradient, in the radial region in which several adjacent modes have been driven unstable, can then further relax because of a slow particle diffusion due to the scattering by the adjacent mode structures.

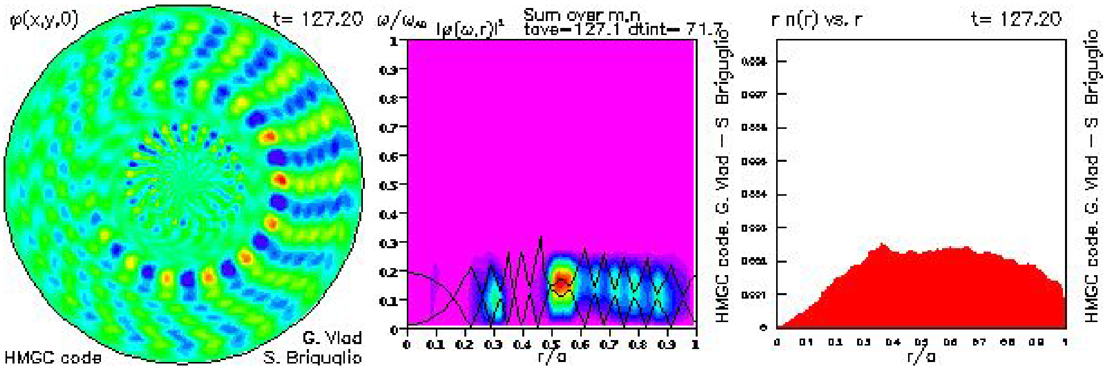

Fig. 3. Saturated configuration for $\beta_H(0) = 0.05$ and the other parameters as in Fig. 2.

We can expect that the consequences of such nonlinear dynamics on the confinement of the energetic ions depend on the capability of the propagated β_H gradient to drive outer modes unstable. This capability depends on the magnitude of the gradient itself, on the structure of the gap in the outer region and on the relative position, in the frequency space, of the gap (minimum damping) and the resonant-excitation (maximum drive) frequencies. The effect of increasing the β_H gradient can be appreciated in Fig. 3, where the saturated-stage configuration is shown for $\beta_H(0) = 0.05$ and the other parameters as in Fig. 2. In this case, the enhanced gradient causes even the outer harmonics to be strongly destabilized (with slightly decreasing frequency following the slope of the gap): there is, in fact, no “insulation” at the minimum-q surface and the convective particle flux reaches the outest flux surfaces.

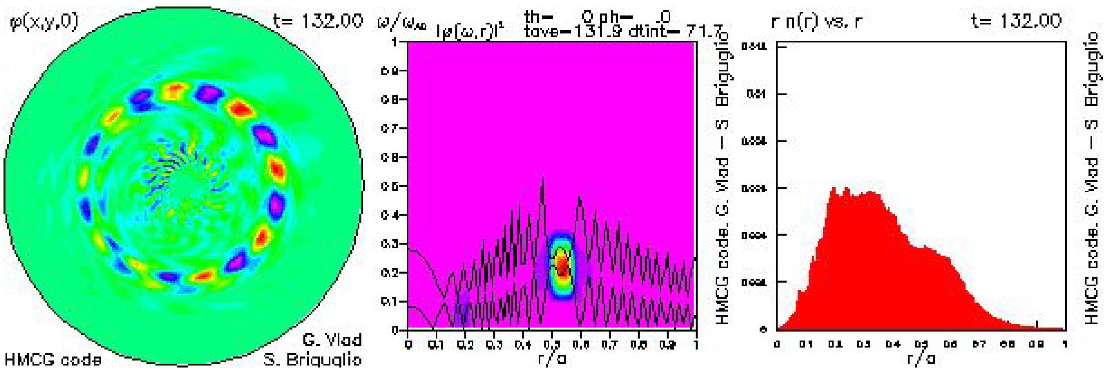

Fig. 4. Saturated configuration for $\beta_H(0) = 0.025$ and deeply hollow q profile.

On the contrary, the insulating effect of a steeper (non aligned) gap is shown in Fig. 4, which refers to the saturated phase for a case with a hollower q profile (profile b in Fig. 1) and $\beta_H(0) = 0.025$. Here, the source displacement produced by the "minimum-q" gap mode saturation [3] is not able to drive any outer mode, and the minimum-q surface encloses a good confinement region. This can be ascribed both to the fact that, at the frequency that should be excited, the radial extension of the gap is too narrow and to the fast increasing ratio between the resonant-excitation and the gap frequencies ($\omega_{dH}/\omega_{GAP} \sim \sqrt{n_0}q^2/r$, with n_0 being the thermal-plasma density). These two factors are removed in the case considered in Fig. 5, where a more realistic thermal-plasma density profile (decreasing as $r \to a$) has been introduced, opening the gap in the outer region. In this case the saturation of the minimum-q gap mode is able to drive outer modes, with higher frequencies, unstable. For such modes the ratio between the maximum-drive and the minimum-damping frequencies does not increase too fast, and a large-drive condition can be satisfied without suffering strong continuum damping, contrary to the case of Fig. 4. In this respect, however, we note that continuum damping for edge-localized Alfvénic modes can be controlled (enhanced) via plasma triangularity in shaped equilibria [4].

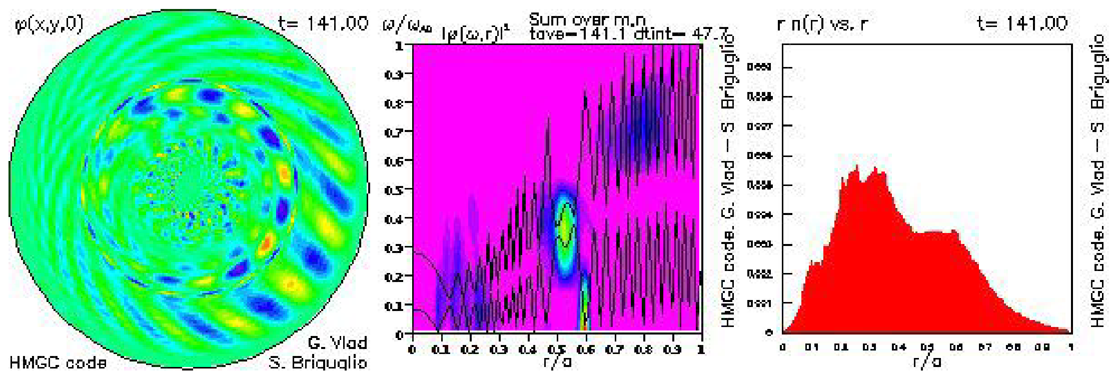

Fig. 5. Saturated configuration for thermal-plasma density decreasing as $r \to a$ and the other parameters as in Fig. 4.

We can conclude that the saturation of EPMs presents a quite rich phenomenology: a gap mode generally survives to the strong, EPM-induced, radial redistribution of the energetic ions. The further particle displacement generated by this mode can induce an avalanche of poloidal harmonic excitation if the propagated β_H gradient gives the drive enough magnitude and the gap structure is sufficiently open to preserve outer modes from strong continuum damping. On the contrary, if the β_H gradient is not sufficiently high and/or the gap is too close in the outer region, both the Alfvénic coherent eddies and the energetic-ion gradient cannot propagate beyond a certain magnetic surface, within which energetic ions are well confined. This is the situation obtained, for example, with deeply hollow q profiles and flat thermal-plasma density profiles, where the minimum-q surface plays the role of the insulating surface. Such a case could give some insights for the interpretation of the results obtained at JET during the current ramp-up phase of Optimized Shear discharges, characterized by hollow q profiles [5].

References

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