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Nonlinear saturation of shear Alfvén modes and self-consistent energetic ion transport in burning plasmas with advanced Tokamak equilibria

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Abstract

Self-consistent nonlinear dynamics of Energetic Particle Modes, which are relevant for burning plasma conditions, are analyzed with respect to both saturation mechanisms and energetic particle transport. It is found that a "sensitive" parameter for Tokamak equilibria with hollow-q profiles is q at the minimum-q surface, higher q corresponding to larger particle transport. This fact has clear implications on the choice of current profiles in a burning plasma.

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Experimental measurements of electromagnetic fluctuations on large auxiliary-heated Tokamak devices [1–4] have indicated the presence of unstable shear-Alfvén modes driven by energetic ions. On JET [3] and JT-60 [4], in particular, such modes have been identified in discharges characterized by hollow q profiles (with q the safety factor). Profiles of this kind are considered with great interest due to the improved confinement regimes that they allow to obtain. However, they can also negatively affect the stability and behavior of Alfvén modes. The large values of q that characterize these profiles in the internal region of the discharge, indeed, yield large energetic-ion orbits and local drive intensity (estimated by the quantity $\alpha_H \equiv -R_0 q^2 \beta_H'$, with R_0 the major radius of the torus, β_H the energetic-ion pressure normalized to the magnetic pressure and "prime" denoting derivation with respect to the radial-flux-coordinate r). Moreover, in a plasma close to ignition conditions, the large power density and profile steepness would yield large values of β_H' and further enhances the energetic-ion drive. Therefore, transport and confinement of fusion-produced alpha particles could be significantly affected by strongly unstable Alfvén modes.

The issue of the stability and dynamics of shear Alfvén modes in a burning plasma with hollow-

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q-profile equilibria requires a fully nonlinear self-consistent (nonperturbative) treatment of the energetic ion dynamics. In this Letter we contribute to this task by analyzing the results obtained with the particle-in-cell Hybrid MHD-Gyrokinetic Code (HMGC) [5,6]. This code allows us to describe, in a self-consistent way, the resonant interaction between Alfvénic modes and energetic ions. For the sake of simplicity, in the specific simulations presented here, we consider full nonlinear wave-particle interactions only, while neglecting nonlinear mode-mode couplings among different toroidal mode numbers n. Moreover, we do not take into account the slow equilibrium evolution—due, e.g., to the current diffusion—, as we are mainly interested in the fast saturation process, which takes places on the scale of $\approx 100\tau_A$ (with $\tau_A \equiv R_0/v_A$ being the Alfvén time and v_A the Alfvén speed).

Fig. 1 shows the initial β_H profile and two different hollow q profiles which are considered in our simulations. All the simulations discussed in this Letter refer to flat energetic-ion temperature profiles and consider the dynamics of $n = 4$ modes. Other fixed simulation parameters are $a/R_0 = 0.1$ (with a being the minor radius of the torus), $\rho_H/a = 0.01$ (normalized energetic ion Larmor radius), $v_H/v_A|_{r=0} = 1$ (energetic ion thermal speed normalized to the Alfvén velocity, on-axis value). Both energetic and thermal ion species are assumed to have the same mass number.

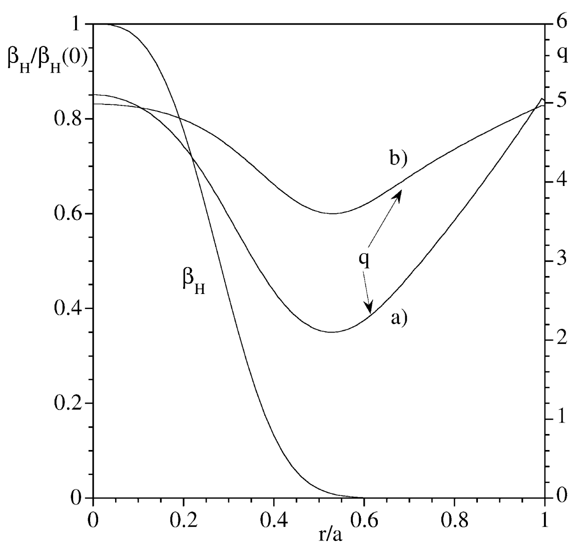

Fig. 1. The two different hollow q profiles and the initial β_H profile adopted in the simulations.

Fig. 2 presents the results relative to the deepest hollow q profile (a in Fig. 1) and $\beta_H(0) = 0.025$. A radially constant thermal-plasma density is assumed, corresponding to a radially constant Alfvén velocity. We observe that an Energetic Particle Mode (EPM) [7], characterized by a real frequency inside the upper continuum (top figure), is driven unstable by the resonant interaction with energetic ions. Its saturation takes place because of a strong, convective, radial displacement of the energetic ions. The maximum of the power spectrum then migrates in frequency towards the toroidal gap and radially outward. This can be understood as follows. The mode forms as the best compromise between maximizing the drive and minimizing continuum damping. Such a compromise is reached by following the outward-moving β_H maximum gradient and properly adjusting the mode frequency. Once the gap is reached (bottom figure), the mode occupies the most favorable location and extension consistent with the radially displaced energetic ion free energy source. This corresponds to a localization around the zero-shear, minimum-q (q_{min}), surface. In the present case, the "q_{min}" gap mode saturates in a softer way without exciting any outer mode, and the q_{min} surface encloses a good confinement region.

The good confinement region observed in Fig. 2 could be ascribed to the stability of the outer region plasma with respect to Alfvénic perturbations or to the lack of efficiency of the gap mode in displacing a strong enough free energy source into that region. The former reason is associated with the strength of continuum damping and the radial width of the frequency gap; the latter depends on the effectiveness of wave-particle interactions, and it is related with the amplitude and the radial width of the mode and with the size of the particle orbits. Here, we determine which is the most relevant among these two factors for the considered hollow q-profile equilibria. Consider first the effect of continuum damping. In Fig. 3, a more realistic thermal-plasma density profile (decreasing as $r \to a$) has been introduced with respect to the case of Fig. 2, making the frequency gap wider in the outer region. This region now is affected by weaker continuum damping: modes with frequency close to the shear Alfvén accumulation point of the upper continuum are observed, corresponding to the upper

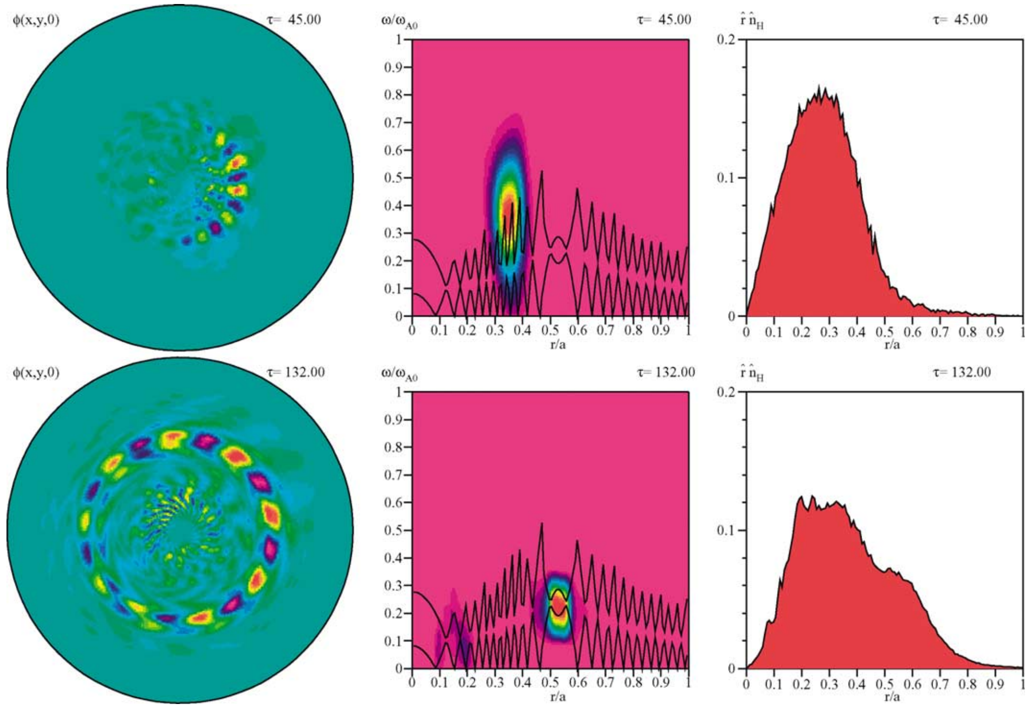

Fig. 2. Contour plot of the scalar potential ϕ at a fixed toroidal angle (left), power spectrum $\sum_m |\phi_{m,n}(r,\omega)|^2$ in the $(r/a, \omega/\omega_{A0})$ plane (center) and energetic-ion line density profile, $\hat{r}\hat{n}_H \equiv (r/a)n_H(r)/n_H(0)$ (right), at two different times: linear growth phase (top; $\tau = 45$) and saturated phase (bottom; $\tau = 132$). Here, $\tau = \omega_{A0}t$ and $\omega_{A0} = v_A|_{r=0}/R_0$. Deeply hollow q profile, radially constant thermal-plasma density and $\beta_H(0) = 0.025$ have been assumed.

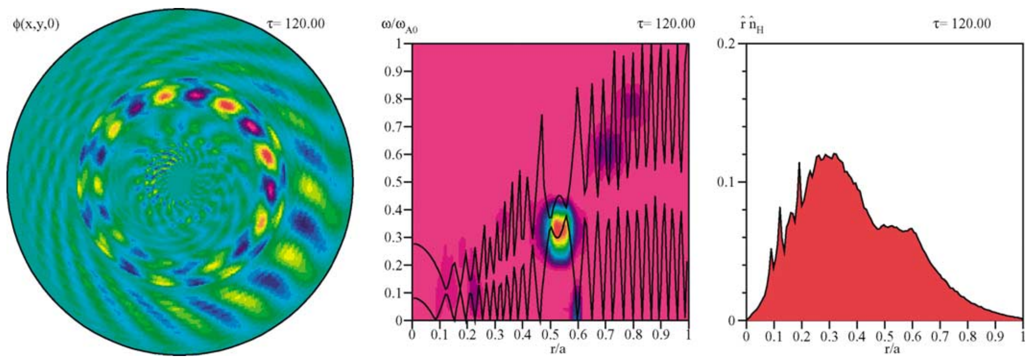

Fig. 3. Saturated phase for a thermal-plasma density profile decreasing as $r \to a$ and the other parameters as in Fig. 2.

branch of Kinetic Toroidal Alfvén modes, which is less damped than the lower one [5]. In spite of this fact, the good confinement of the energetic ion population is not lost. We can conclude that, at least for the case examined here, the energetic-particle transport is mainly inhibited by the mode-particle interaction at the q_{min} surface.

The interaction between the gap mode and the energetic particles can be trivially enhanced by increasing the initial value of the β_H gradient (i.e., the source of instability). This is shown in Fig. 4, which refers to the saturated phase for the case with $\beta_H(0) = 0.05$ and the other parameters as in Fig. 2. For such a high value of energetic-particle drive, the linear growth-rate

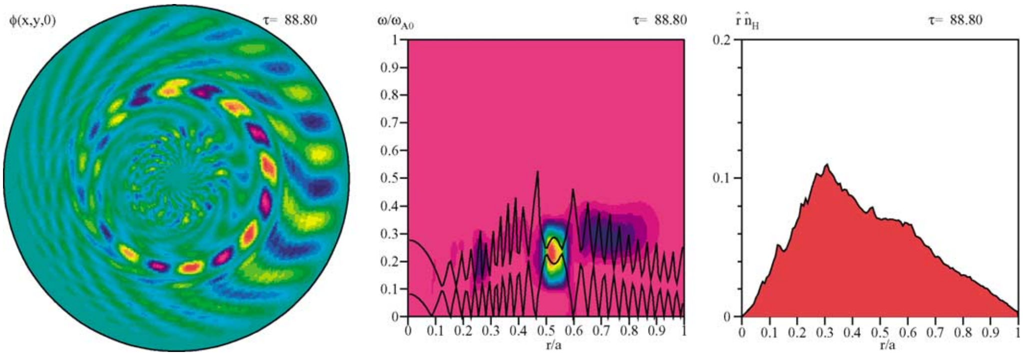

Fig. 4. Saturated phase for $\beta_{\mathrm{H}}(0)=0.05$ and the other parameters as in Fig. 2.

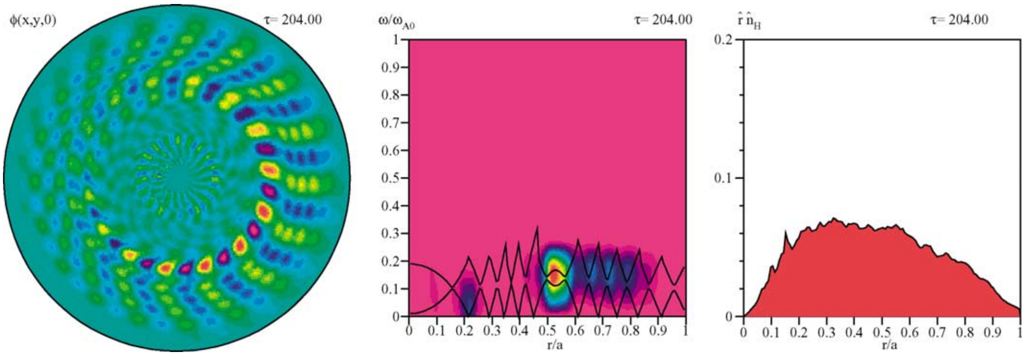

Fig. 5. Saturated phase for moderately hollow q profile and the other parameters as in Fig. 2.

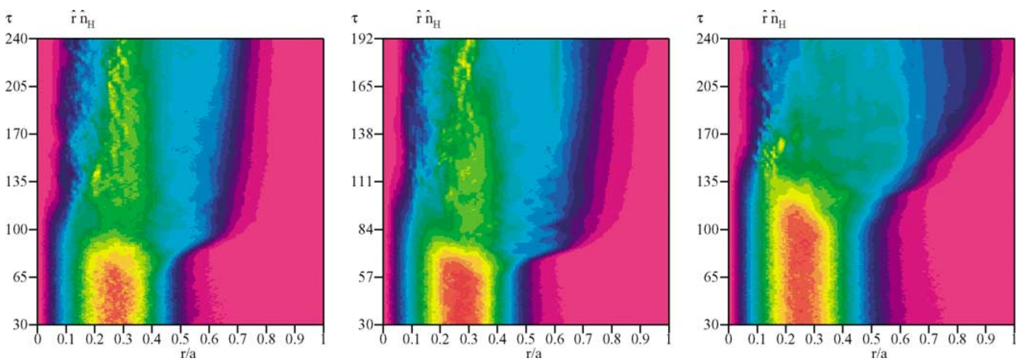

Fig. 6. Contour plot of the normalized line density, $\hat{r}\hat{n}_{\mathrm{H}}$, of energetic ions in the $(r/a,\tau)$ plane for the three low-β_{H} ($\beta_{\mathrm{H}}(0)=0.025$) cases: the deeply hollow q-profile case, with flat (left) or decreasing thermal-plasma density (center), and the moderately hollow q-profile case (right).

of the EPM is larger than in the previous cases, resulting in radially broader mode structures. Similarly, the mode amplitude reached at saturation is larger than that of the lower β_{H} case shown in Fig. 2. Both effects yield a larger energetic-ion displacement which, in turn, drives outer poloidal harmonics unstable, with frequency close to the upper continuum. Transport of energetic ions increases in the outer region, although their global confinement is not substantially degraded.

A much more dramatic effect can be obtained by acting on the q profile. The reason for this is that, for a given value of β'_{H}, the mode radial width scales, near the $q_{\min}$ surface, as $1/\sqrt{nq''}$, while the typical orbit size is proportional to $q_{\min}$. Decreasing the hollowness of the q profile, while taking $q(0)$ and $q(a)$ fixed, yields lower q'' and larger $q_{\min}$ values, and makes both the mode and the orbit widths larger than in the deeply-hollow q-profile case. Moreover, the energetic-ion drive intensity, α_H, scales as $q_{\min}^2$. The mode is then a more efficient scattering source for energetic-ion orbits even in the relatively low β_H case. This fact and the fair alignment of the frequency gap at different radial positions make the displaced energetic ion source effective in destabilizing an avalanche of outer poloidal harmonics. This is shown in Fig. 5, which represents the saturated phase obtained with a moderately-hollow q profile (profile b in Fig. 1) and $\beta_H(0) = 0.025$. It can be seen that the confinement of the energetic particle population is significantly degraded. This can be better seen from Fig. 6, where the space–time contour plot of the energetic ion line density is plotted in the $(r/a, \tau)$ plane for the three low-β_H cases discussed above. The degradation of energetic ion transport at the $q_{\min}$ surface is apparent in the moderately hollow q-profile case (right).

We can conclude that the saturation of EPMs presents a quite rich phenomenology. After the initial destabilization of an EPM within the $q_{\min}$ surface, a gap mode [8] generally survives to the strong, EPM-induced, radial redistribution of the energetic ions. If the particle orbits are poorly affected by the interaction with the $q_{\min}$ gap mode and the gap is narrow in the outer region, both the Alfvénic coherent eddies and the energetic-ion gradient cannot propagate beyond a certain magnetic surface, within which the energetic ions are well confined, giving a “barrier” in the sense of transport. On the contrary, in the presence of an effective mode-particle interaction at the $q_{\min}$ surface, a significant fraction of the energetic ion population is displaced outside this surface. If the gap structure is sufficiently open to preserve outer modes from strong continuum damping, the displaced instability source can induce a strong excitation of outer poloidal harmonics and degradation of the energetic-ion confinement. Crucial control parameters in determining the fast ion transport across the $q_{\min}$ surface, besides β_H' (the obvious one), are q'', which reflects on the local mode width ($\propto 1/\sqrt{nq''}$), and $q_{\min}$ itself, as the typical orbit size is proportional to q and the energetic-ion drive intensity scales as q^2. These facts explain the better energetic ion confinement obtained, *ceteris paribus*, with deeply hollow q profiles, for which the $q_{\min}$ surface acts as a transport barrier.

The present analysis provides detailed insights into the properties of fusion product transport induced by collective modes of the Alfvén branch that can be expected in a burning plasma operating in advanced scenarios (e.g., ITER [9]). In fact, the peaked thermal plasma profiles that are expected in such scenarios within the $q_{\min}$ surface, result in an even more pronounced peakness of fusion product energy density that could yield EPM excitation. In this respect, this work gives useful information for the optimal choice of q (and, thus, plasma current) profiles.

References

[1] W. Heidbrink, Plasma Phys. Controlled Fusion 37 (1995) 937.
[2] S. Bernabei, M. Bell, R. Budny, D. Darrow, E. Fredrickson, N. Gorelenkov, J. Hosea, R. Majeski, E. Mazzucato, R. Nazikian, C. Phillips, J. Rogers, G. Schilling, R. White, J. Wilson, F. Zonca, S. Zweben, Phys. Plasmas 6 (1999) 1880.
[3] D. Testa, F. Zonca, S. Briguglio, L. Chen, S. Dettrick, G. Vlad, A. Fasoli, A. Gondhalekar, Contributors to the EFDA-JET work programme, in: EPMs in JET Optimized Shear Experiments with non-monotonic q-profiles, in: EPS Conf. 2001, Madeira, Portugal, 2001.
[4] K. Shinohara, Y. Kusama, M. Takechi, A. Morioka, M. Ishikawa, N. Oyama, K. Tobita, T. Ozeki, S. Takeji, S. Moriyama, T. Fujita, T. Oikawa, T. Suzuki, T. Nishitani, T. Kondoh, S. Lee, M. Kuriyama, JT-60 Team, G. Kramer, N. Gorelenkov, R. Nazikian, C. Cheng, G. Fu, A. Fukuyama, Nucl. Fusion 41 (2001) 603.
[5] S. Briguglio, G. Vlad, F. Zonca, C. Kar, Phys. Plasmas 2 (1995) 3711.
[6] S. Briguglio, F. Zonca, G. Vlad, Phys. Plasmas 5 (1998) 3287.
[7] L. Chen, Phys. Plasmas 1 (1994) 1519.
[8] H. Berk, D. Borba, B. Breizman, S. Pinches, S. Sharapov, Phys. Rev. Lett. 87 (2001) 185002.
[9] ITER Physics Basis Editors, et al., Nucl. Fusion 39 (1999) 2137.