Structure of wave-particle resonances and Alfvén mode saturation

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The dynamics of beta-induced Alfvén eigenmodes driven by anisotropic co-passing or counter-passing fast ions, in a low-shear magnetic equilibrium, is investigated by self-consistent hybrid MHD-particle simulations with the XHMGC code. Though the modes exhibit similar structure and frequency in both cases and the linear growth rate is 10% larger for counter-passing ions than for co-passing ions, the nonlinear saturation amplitude is much larger in co-passing case. Moreover, different scalings for the saturation amplitude with increasing growth rates are observed in the two cases. It is shown that these differences are caused by the different radial dependence of resonance frequencies of co-passing and counter-passing fast ions: flat in the former case, steep in the latter case, so that the resonance width is, respectively, larger (in the former case) or smaller (in the latter case) than the mode width. [http://dx.doi.org/10.1063/1.4940785]

I. INTRODUCTION

Shear-Alfvén modes can be driven unstable, in burning plasmas, by the resonant interaction with energetic ions produced by additional heating or nuclear fusion reactions. These particles are indeed characterised by velocities of the order of the Alfvén speed, the typical propagation velocity of those modes. The Alfvénic fluctuations generated in this way can in turn affect the confinement of energetic ions, preventing their complete thermalization in the central region of the plasma and, possibly, increasing the thermal load on the material wall surrounding the plasma. The assessment of energetic particle confinement properties in next generation fusion experiments then strongly relies on the comprehension of Alfvén mode dynamics, with regard both to the linear stability properties (which modes are expected to be driven unstable) and the nonlinear saturation mechanisms (which saturation level is expected for the mode amplitude and which effect on the fast ion confinement).

The relevance of these issues has motivated a very rich literature on the side of linear stability investigation. In general, the saturation mechanisms of Alfvén eigenmodes (AE) can be classified into two major categories: fluid mode-mode coupling and nonlinear wave-particle interactions. Although the former can play a crucial role in multi-scale dynamics of burning plasmas, we will focus, in the current paper, on the latter category, motivated by the relevance of the resonant drive on the Alfvénic fluctuation spectrum in fusion devices. Most nonlinear studies concerning wave-particle dynamics have been focused on two extreme limits: weak Toroidal Alfvén Eigenmodes (TAEs) close to marginal stability and Energetic Particle Modes (EPMs) strongly driven by large gradients of fast ion pressure. It has been shown that the former modes saturate because of phase mixing of resonant particles trapped in the potential well of the wave (i.e., gradient flattening on the length scale of the mode), reducing the wave-particle power transfer. In this near-marginal stability regime, the radial excursion of fast ions due to the mode-particle interaction is so limited that it does not allow resonant particles to perceive any of the (equilibrium or fluctuation induced) non-uniformities characterizing the system. This fact may result in the formation of phase-space holes and clumps and adiabatic frequency chirping due to resonant frequencies following hole and clump propagation, as discussed in Refs. 14–17. Strongly driven EPMs saturate instead of large radial displacement of resonant particles (a potentially large fraction of the whole population), with consequent macroscopic distortion of the energetic particle pressure profile. It has been shown that this mechanism, with an outwardly moving front of pressure gradient, can give rise to avalanches: oscillations of the shear-Alfvén continuous spectrum are driven progressively unstable by the drifting free energy source. In this non-perturbative, strongly driven regime, the radial excursion of resonant particles is so essential that it self-consistently determines the nonlinear mode structure evolution.

The transition between these two limiting behaviours has been less explored, though it is likely that burning plasmas will be characterised by shear-Alfvén modes in an intermediate dynamic regime. In Ref. 19, this issue has been investigated by applying test-particle diagnostics to the analysis of nonlinear resonant particle dynamics. Two different cases were considered in that paper: a $n = 6$ TAE (with $n$ being the toroidal mode number) in a low magnetic shear equilibrium and a $n = 2$ EPM in a plasma equilibrium with larger shear. It has been shown that, in the former case, saturation is due to a mechanism called radial decoupling, with the radial mode structure playing a major role; in the latter, saturation is caused by a mechanism called resonance detuning, dictated by the finite radial width of the region where particles can effectively resonate with the mode.
In the current paper, we want to show that these two different mechanisms can occur even for a single plasma equilibrium and a particular Alfvén eigenmode with a particular toroidal mode number \( n \), in situations which, from a macroscopic point of view (that is, looking at the mode-particle interaction integrated over the whole energetic-particle distribution) may appear to be characterised by analogous linear behaviour. To this aim, we will present the results of a numerical investigation related to the linear and nonlinear evolution of beta induced Alfvén eigenmodes (BAEs). The experimental observation\(^{21,22}\) of these low-frequency modes (with frequencies lower than those of TAEs, and of the order of the thermal-ion diamagnetic or transit frequency) has demonstrated that they can be deleterious for fast-ion confinement. Thus, BAE dynamics is an important topic for the understanding of magnetically confined plasma behaviour.

The investigation of BAEs requires a proper kinetic treatment of wave-particle interactions, both for energetic and thermal particles.\(^{23,24}\) In the frequency range where kinetic thermal-ion response affects the structure of the shear-Alfvén continuum and influences plasma dynamics,\(^{1}\) there is a continuous transition between various shear-Alfvén wave (SAW) branches, as predicted theoretically\(^ {1,12,24–30}\) and confirmed experimentally.\(^ {21,31–39}\) A theoretical analysis of the linear stability of BAEs has been carried out\(^ {40}\) in the framework of the so-called generalized fishbone like dispersion relation (GFLDR),\(^ {11,27,41–43}\) while, in that paper, only some aspects of the nonlinear dynamics of these modes have been explored.

In the current work, we will investigate the nonlinear wave-particle interactions for BAEs driven unstable by fast ions characterised by anisotropic Maxwellian distribution functions, by means of numerical simulations performed by a hybrid magnetohydrodynamics-particle code (XHMGC).\(^ {44–46}\) We will analyse two cases with co-passing and counter-passing energetic ions, respectively. The results can be summarized as follows. While the co-passing and counter-passing ion cases present similar linear-dynamics mode features (in particular, similar mode frequencies and radial mode structures), the mode saturation amplitude, in the weak-drive limit, is significantly larger for the co-passing fast ion case than the counter-passing one, in spite of the 10% larger growth rate observed in the latter case. Moreover, for co-passing ions, a linear dependence of the saturation amplitude on the mode growth rate is found: for counter-passing ions, a quadratic scaling is obtained in the weak-drive limit, along with a transition to a linear scaling in the strong-drive limit. In the latter limit, saturation amplitudes for co-passing and counter-passing ion cases converge to the same value. In order to explain these differences, a detailed analysis of the resonant interactions between mode and fast ions is performed by looking at phase-space slices characterised by fixed values of constants of motions. Mode-particle interactions then have a “local” character, in the sense that particles belong to the same phase space slice throughout the nonlinear dynamics; and each phase space slice yields its own contribution to mode dynamics; the time evolution of such contribution can be analysed independently of the others. Considering the phase space slice where the maximum resonant interaction is localised, it is shown that resonant frequencies of co-passing and counter-passing fast ions have different radial dependences, because of their different orbits in the non-uniform tokamak equilibrium. Although mode saturation is reached, in both cases, because of resonant-ion density flattening, in the co-passing ion case, the resonance width is very large, and the width of the flattening region required for reaching mode saturation is of the order of the smaller mode width (saturation due to radial decoupling). For counter-passing ions, in the low growth rate limit, the resonance width is much smaller than the mode radial extension and represents the relevant limit for the flattening region at saturation (saturation due to resonance detuning); for larger growth rates, a transition to the radial decoupling regime is observed. On the basis of a simple model, we find that resonance detuning and radial decoupling regimes correspond to different expressions of the saturation amplitude on mode width, growth rate, and radial slope of the resonance frequency. These expressions reproduce quite well the ratio between saturation amplitudes in the co-passing and counter-passing ion simulations, as well as the scaling of such amplitudes with the growth rate.

The paper is organized as follows. In Section II, we describe the numerical method and the main elements of the system considered in our BAE simulations, including thermal plasma and co-passing and counter-passing fast ion populations. In Section III, linear dynamics of resonantly excited BAE are analysed, with respect to both macroscopic mode characteristics and microscopic resonant-particle features. In Section IV, nonlinear dynamics are discussed along with the different properties of the saturation state in the two considered cases. The heuristic model is presented in Section V. Finally, summary and conclusions are presented in Section VI.

II. NUMERICAL METHOD AND SIMULATION PARAMETERS

The extended version of the nonlinear hybrid magnetohydrodynamics-gyrokinetic code (XHMGC)\(^ {44–46}\) has been used to simulate self-consistently the BAE driven by fast ions characterised by anisotropic-Maxwellian distribution functions. Within this hybrid model, the fluid response of the thermal background plasma is described by a set of \( O(\epsilon^3) \)-reduced MHD equations for a low-\( \beta \) plasma, and the fast-ion and thermal-ion kinetic dynamics enter via the pressure tensors, which are computed by solving the gyrokinetic equations, in the drift-kinetic limit, by particle-in-cell techniques. Finite-Larmor-radius effects are ignored, while finite-orbit widths are taken into account in order to retain resonant wave-particle dynamics associated with guiding-center magnetic-curvature drift in toroidal geometry. Assuming cold electrons, ideal-MHD Ohm’s law \((E_\parallel = 0)\) could be considered; but XHMGC requires a small resistivity, for numerical reasons. In the present study, we ignore thermal-ion diamagnetic effects by assuming uniform thermal-ion density and temperature; we instead keep kinetic thermal-ion compressibility effects, in order to include the formation of a kinetic thermal-ion gap. Finally, a single toroidal mode number, \( n = 2 \), is retained in the following simulations: this corresponds to neglecting fluid mode-modal
coupling in the evolution of electromagnetic fields, while fully taking into account wave-particle nonlinearities.

A tokamak equilibrium with shifted circular magnetic surfaces is considered, with aspect ratio $R_d/a = 10$ and safety factor $q \approx q_0 + (q_a - q_0)(r/a)^2$, with $q_0 = 1.9$, $q_a = 2.3$ as shown in Fig. 1(a). Thermal ions are characterised by isotropic Maxwellian initial distribution function with flat density and temperature profiles. The fast (“hot”) ion (same species as the thermal ones) initial distribution function is instead an anisotropic Maxwellian in the form

$$F_H \propto \frac{n_H(\psi)}{T_H^{3/2}} \Xi(x, x_0, \Delta) e^{-E/T_H}.$$  \hspace{1cm} (1)

Here, $E = \frac{1}{2} m_H U^2 + M \Omega_H$ is the particle energy, $n_H(\psi)$ is the density profile, shown in Fig. 1(b), $U$ is the parallel to the equilibrium magnetic field) velocity, $M$ is the conserved magnetic momentum, $x \equiv \cos^{-1}(U/\sqrt{2E/m_H})$, $\Omega_H = e_H B / (n_H c)$ is the cyclotron frequency, with $e_H$ and $m_H$ being charge and mass of fast ions, respectively, and $B$ is the magnitude of local equilibrium magnetic field. The quantity

$$\Xi(x, x_0, \Delta) \equiv \frac{4}{\Delta^{1/2}} \frac{\exp \left[ - (\cos x - \cos x_0)^2 / \Delta^2 \right]}{\text{erf} \left( (1 - \cos x_0) / \Delta \right) + \text{erf} \left( (1 + \cos x_0) / \Delta \right)}$$  \hspace{1cm} (2)

models the anisotropy of the distribution function. Note that, in the isotropic limit ($\Delta = 1$), $T_H$ would assume the meaning of (uniform) temperature. In the present case, we assume an anisotropic initial distribution function characterised by parallel temperature much higher than the perpendicular one, by fixing $\Delta = 0.1$ and $x_0 = \cos^{-1}(1/2)$ or $x_0 = \cos^{-1}(-1/2)$ for co-passing and counter-passing fast ions, respectively. These distribution functions are shown in Figs. 2(a) and 2(b), respectively. Other parameters are $v_H/a_0 = 0.3$, $v_A/a_0 = 0.06$, $\rho_H/a = 0.01$, and $\rho_A/a = 0.002$, with $\rho_H \equiv v_H / \Omega_H$, $\rho_i \equiv v_i / \Omega_i$, $\Omega_i$ being the thermal ion cyclotron frequency, $v_A$ the Alfvén velocity, and the subscript “0” corresponding to quantities computed at the magnetic axis. Note that the initial distribution function is not a proper equilibrium function, as it is not merely a function of constants of the unperturbed motion. For simplicity, we neglect the consequent initial relaxation of $F_H$ towards a genuine equilibrium, by suppressing the corresponding terms in the evolution of the perturbed distribution function $\delta F_H$; this does not affect our results in a significant way, as the typical particle orbit width (which causes $\psi$ not being a constant of the unperturbed motion) is few percent of the minor radius. In the following, for linear simulations, we shall consider a fraction of fast ions, $n_H/n_0$, ranging in the interval $[0.0014, 0.002]$; for nonlinear

FIG. 1. The radial profile of safety factor (a) and normalized EP density radial profile $n_H/n_{H_0}$ (b).

FIG. 2. Contour plot of the initial distribution function in the velocity space for co-passing (a) fast ions and counter-passing, (b) fast ions. Note that $M$ and $U$ are reported in units of $T_0/\Omega_0$ and $\sqrt{T_H/m_H}$. Passing-trapped boundaries evaluated at the inner ($r/a = 0.2$, dashed) and outer ($r/a = 0.8$, solid) limits of the mode’s radial domain are shown.
Simulations, we shall analyse only the weakest case, $n_{i0}/n_0 = 0.0014$. In all the simulations, poloidal harmonics with $m$ from 1 to 6 will be retained.

### III. LINEAR DYNAMICS

#### A. Overview of linear evolution

In the absence of thermal-ion kinetic effects, the accumulation point on the shear Alfvén continuum at the rational surface would correspond to a frequency $\omega_{acp} = 0$. Once those effects are taken into account, the accumulation point moves to a finite frequency value. In this case, the radial dependence of the shear Alfvén continuum frequency has been computed, for the equilibrium here considered, by the linear gyrokinetic eigenvalue code LIGKA.\(^{47}\) It is shown in Fig. 3 by the red curve; curves corresponding to $T_e = T_i$ (black) or the absence of kinetic thermal-ion effects (blue) are also reported, for comparison. When fast-ion drive is included, XHMG simulations show the existence of an unstable BAE mode, with frequency in the kinetic thermal-ion gap, very close to the shear-Alfvén continuum accumulation point, as shown in Fig. 4. Both co-passing and counter-passing fast ions drive the mode unstable via transit resonance, with the same real frequency. The growth rates increase with increasing fast-ion fraction; those associated to counter-passing ions are approximately 10% larger than those associated to co-passing ions, as shown in Fig. 5. The radial structure of different poloidal harmonics is shown in Fig. 6 for the co-passing and counter-passing ion cases: differences between the two cases are negligible.

In order to analyse wave-particle interactions in greater detail, we can look at the particle-to-wave power transfer. Once averaged over poloidal ($\theta$) and toroidal angle ($\phi$), and weighted with the fast-ion distribution function, its density in the reduced phase space ($r, M, U$) can be written as\(^{19}\)

$$P(r, M, U) \equiv -2\pi \int d\theta d\phi D_z \frac{dE}{dt} \sum_I p_i \delta(r - r_I) \delta(M - M_I) \delta(U - U_I), \quad (3)$$

where $D_z \rightarrow Z$ is the Jacobian of the transformation from canonical to guiding-center coordinates, $Z \equiv (r, \theta, \phi, M, U)$, and the latter expression for $P(r, M, U)$ represents its discrete form, as a sum over the simulation macroparticle population. In Fig. 7, the power transfer density $P(r, M, U)$, integrated over a radial shell centred around the mode peak, is shown for co-passing and counter-passing fast-ion cases. We

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**Fig. 3.** Shear Alfvén continuum for the equilibrium considered in the present paper, calculated by LIGKA (red curve). The same continuum for $T_e = T_i$ (instead of $T_e = 0$) and in the absence of thermal ion effects are represented by black and blue curves, respectively. The accumulation-point frequencies for the former two cases are indicated by red ($\omega = 0.125 \omega_{a0}$) and black ($\omega = 0.15 \omega_{a0}$) lines, respectively, with $\omega_{a0} \equiv v_{a0}R_0$ being the on-axis Alfvén frequency.

**Fig. 4.** Energy spectrum for the scalar potential, in the ($r$, $\omega$) plane, for the BAE driven by fast ions with $n_{i0}/n_0 = 0.0014$. The solid line represents the shear Alfvén continuum with thermal-ion kinetic effects included. The mode is located in the thermal-ion gap. (a) co-passing particles and (b) counter-passing particles.
observe that contour plots, in the two cases, are almost symmetric with respect to parallel velocity. Figure 8 shows the similarity of the two cases subsists also with respect to the radial profile of the power transfer density integrated over the whole velocity space.

B. Resonance analysis

Differences between the two cases become evident only in a detailed analysis of the resonant particle behaviour. Following Ref. 19, we observe that, in the presence of an electromagnetic field perturbation characterised by a single toroidal number and constant frequency, the quantity

\[ \frac{C}{C_1} \frac{P}{P_0} \times nE \]

with \( P \) being the toroidal angular momentum, is a constant of the (perturbed) motion. At the leading order,

\[ P' = mHRU + eHR_0 (\psi_{eq} - \psi_{eq0})/c, \]

with \( \psi_{eq} \) defined by \( B = R_0 B_{\phi0} \nabla \phi + R_0 \nabla \psi_{eq} \times \nabla \phi \). Then, if we cut the phase space into “slices” of given constant of motions \( M \) and \( C \), particles remain in the same slice during the whole evolution of the system. The wave-particle power exchanges within different slices are then independent of each other, and the analysis of a single-slice behaviour gives us a microscopic view of the mode-particle dynamics, possibly hidden to a macroscopic (that is, integrated) inspection.

In order to explore dynamics within a single slice (and, in particular, the characteristic particle frequencies; namely, bounce/transit frequency \( \nu_b \) and precession frequency \( \omega_p \)), we sample that slice by means of a set of test particles...
evolved in the self-consistently simulated fields. The selection of test particles is discussed in detail in Ref. 19. Once a significant couple, \((M_0, C_0)\), is identified, corresponding to a power-transfer peak in the linear phase, we initialise a set of test particles with \(M = M_0, C = C_0\) and \(h = 0\) (that is, on the equatorial plane). Each particle has a different radial coordinate \(r\) and the corresponding value of \(U = U(r, h = 0, M_0, C_0)\). Such a set is then replicated at different values of the toroidal angle \(\phi\).

For each particle, we can compute \(\omega_b\) and \(\omega_D\) by collecting particle information every time the particle crosses the equatorial plane \((h = 0)\) at its outmost \(R\) position (in the following, we shall use the attribute “equatorial-plane” to refer to such condition). The resonance frequency is given, as a combination of these characteristic frequencies, by

\[
\omega_{\text{res}} \equiv n \omega_D + [(nq - m)\sigma + k]\omega_b.
\] (4)

Here, \(\sigma = \text{sgn}(U)\),

\[
\omega_b \equiv \frac{2\pi}{\tau_b},
\] (7)

where \(\Delta\phi\) is the change in toroidal angle over the bounce time \(\tau_b\) (the time needed to complete a poloidal orbit), defined as

\[
\tau_b \equiv \oint \frac{d\theta}{\dot{\theta}},
\] (8)

and \(\bar{q}\) is the safety factor integrated along the particle orbit

\[
\bar{q} \equiv \frac{\sigma}{2\pi} \oint q d\theta.
\] (9)

The resonance frequency can be represented, for the set of test particles, as a function of the equatorial-plane radius only. Figure 9 reports \(\omega_{\text{res}}(r)\) for different values of the bounce harmonic \(k\) and \(\bar{q}\).

FIG. 8. Radial profile of the linear-phase power transfer density \(P(r, M, U)\) integrated over the whole velocity space, for co-passing (a) and counter-passing (b) fast ions.

FIG. 9. Resonance frequency, \(\omega_{\text{res}}(r)\) for co-passing (a) and counter-passing (b) fast ions, for different values of the bounce harmonic \(k\). The relevant bounce harmonic for both co-passing particles and counter-passing particles is \(k = 1\).
bounce harmonic $k$, along with the effective mode frequency. It can be seen that the relevant bounce harmonic for both co-passing and counter-passing particles is $k = 1$. The various ingredients entering the resonance frequency for co-passing and counter-passing test-particles are shown in Fig. 10. Both the bounce frequency, $\omega_b$, and the factor $(nq - m)\omega_b$ have similar profiles for the two test-particle sets. The precession frequency, $\omega_D$, is negligible in both cases. The opposite sign of the parallel velocity, $\sigma$, however, makes the $\omega_{res}$ profiles very different; in particular, co-passing test particles have a much flatter profile, especially in the inner radial region.

The resonance condition $\omega - \omega_{res}(r, M_0, C_0, k) = 0$ identifies an equatorial-plane radial position $r = r_{res}(\omega, M_0, C_0, k)$ where the resonance takes place. If the mode is characterised, in the linear phase, by a growth rate $\gamma$, the resonance will be anyway significant in a radial layer around $r_{res}$, approximately defined by the following condition:

$$|\omega - \omega_{res}(r, M_0, C_0, k)| \leq \gamma.$$  

(10)

The resonance width is larger for larger growth rates and/or weaker radial dependence of $\omega_{res}$. In Fig. 11, the determination of the layer is reported for co-passing and counter-passing ions. In the considered case, the two species behave differently due to the different sign of their velocity, which yields a different radial dependence of the resonance frequency: co-passing ions are characterised by a large resonance width, because of the flat radial profile of $\omega_{res}$; counter-passing ions have instead a narrow resonance, due to the much steeper $\omega_{res}$ profile. In Sec. IV, we will show that this difference causes the different nonlinear evolution of the mode amplitude in the two cases.

The radial density of power transfer, for the considered slice, can be qualitatively represented by the following symbolic form:

$$P(r, M_0, C_0) \sim \left\langle \sum_{Z} \left[ \frac{D_{Z} - \frac{i}{2}}{\omega + i \gamma - \omega_{res}} \right] \left[ \frac{d \bar{Z}}{dt} \right] \frac{\partial F_j}{\partial \bar{Z}} \right\rangle \times \left[ \frac{d \bar{Z}}{dt} \right] \frac{\partial E}{\partial \bar{Z}}.$$  

(11)
Here, we have adopted a coordinate system $\tilde{Z} = (r, \theta, \phi, M, C)$, and the subscript “1” stands for the perturbed part of the phase-space velocities, proportional to the perturbed fields. The average is performed by integrating each test particle contribution along the last poloidal orbit (that connecting two successive equatorial-plane crossings) and summing the results over the class of test particles characterised, on the equatorial plane, by the same value of $r$ and different values of $\phi$. This simplified form makes clear that the effective power exchange structure is determined not only by the resonance condition (Eq. (10)), but also by the spatial mode structure and the distribution-function gradients computed in the resonant region. Note that, once the coordinate system $\tilde{Z}$ is adopted and provided the conditions for $C$ conservation are satisfied, gradients with respect to $M$ and $C$ do not enter the power exchange, as the corresponding phase-space velocities are zero. Then, the main free-energy source for instability comes, at the lowest order, from the radial derivative of $F_{H}$. Looking at the two factors directly related to the existence of a perturbed field (mode structure and resonant layer), we see, from Fig. 12, that the co-passing ion case and the counter-passing ion case fall into two different limits. For co-passing ions, the resonance width is larger than the mode width, which then yields the most restrictive constraint to the power transfer radial extension. On the contrary, for counter-passing ions, the main constraint comes from the resonance width (smaller than the mode width). A more stringent limitation could be set by the width of the region where the radial gradient of the initial distribution function for $M = M_0$ and $C = C_0$ is relevant, if such width is smaller than both mode and resonance ones. This is not the case, however, in the considered scenario: the gradient width comes out to be slightly larger than the mode width. In Sec. IV, we will analyse how the linear-dynamics features described in the present section determine the nonlinear evolution of modes in the co-passing and counter-passing ion cases.

IV. NONLINEAR DYNAMICS

Figure 13 shows the nonlinear evolution of the perturbed scalar potential amplitude, in the weakest case reported in Fig. 5 ($n_H/n_i = 0.0014$), for both co-passing and counter-passing fast-ion drive. Saturation is reached at a larger amplitude in the co-passing fast-ion case than the counter-passing one, in spite of a smaller growth rate. Looking only at macroscopic mode and particle linear-dynamics features, such as mode frequency (Fig. 4) and structure (Fig. 6) or radial profile of the integrated (over the velocity space) power transfer (Fig. 8), very similar in the two cases, this result could seem counterintuitive; also because the transition from linear to saturation phase is not accompanied, in any of the two cases, by significant modification of mode frequency (Fig. 14) and structure (Fig. 15) or fast-ion density profile (Fig. 16). We have already seen, however, in Sec. III B, that the phase space can be discretised into slices of constant $M$ and $C$, with particles belonging to each slice being conserved. The integrated mode-particle power exchange can then be seen as the collective effect of the different slices, each of them evolving in an independent way.

The analysis of a single slice corresponding to a peak of resonant drive (in the following, a “resonant slice”) has shown that the two cases deeply differ with respect to the radial profile of the resonance frequency. This causes the radial

FIG. 12. Resonance radial structure compared with the mode structure (red solid curve) and the effective power transfer one (black dashed curve), for the co-passing (a) and counter-passing (b) fast-ion selected sets. The radial extension of power transfer density is limited by mode radial width for co-passing ions; by resonance width, for counter-passing ions.

FIG. 13. Time evolution of the normalised scalar potential amplitude $|\phi/T_H|$ at the peak of the mode structure.
extension of the power transfer to be limited by the mode width, in the co-passing ion case; by the resonance width, in the counter-passing ion case.

In Ref. 19, it has been shown that following the evolution of test particles belonging to a resonant slice, by means of Hamiltonian mapping techniques, allows for identifying the mode saturation mechanism (cf. the Appendix for a short description of the method). In particular, it has been described the formation of topologically closed particle orbits in the plane $\left(\Theta, P_\Phi\right)$ (with $\Theta$ being the wave-particle phase) around the resonance condition, $P_\Phi = P_{\Phi, \text{res}}$, because of the mode-particle interaction. The consequent mixing of particles originating from the higher-density side of the resonance with particles originating from the lower-density one produces density profile distortions. In the following, we shall indicate such process as “density flattening,” although it can even consist in a density-profile inversion and it is accompanied by a density steepening at the boundaries of the interested region.

Saturation is reached when the density flattening covers the whole effective power-transfer region, determined by the coexistence of mode strength and frequency matching. Note that this would be true even in a case (different from the scenario considered in this paper), in which the power transfer region in the linear phase was limited by the finite radial extension of an equilibrium fast ion density gradient narrower than mode and resonance width. Indeed, in such case, the large gradients built by the density profile evolution on both sides of the flattening region would be able to yield the
free-energy source for driving the mode even in where, in the linear phase, the gradient was negligible. In other words, the original narrowness of the gradient region would not play any role in limiting the evolution of the density profile: such evolution would eventually stop only when facing the bounds posed by mode or resonance width.

Figure 17 compares the test-particle density profile at saturation with the unperturbed one. It can be seen that the width of the density-flattening region is much larger for co-passing ions than for counter-passing ones. This is consistent with the fact that, in the co-passing ion case, the power-transfer region is limited by the mode width; for the counter-passing ions, it is limited by the (smaller) resonance width. Figure 18 reports a comparison between the radial width of resonance, mode structure, and density-flattening region for co-passing and counter-passing ions, at different values of the linear growth rate. In the former case, the width of the saturation flattening region is limited by the mode width. In the latter case, it is limited by the resonance width in the low-γ limit; by the mode width, in the large-γ limit.

Figure 19 shows the saturation field amplitude obtained, for co-passing and counter-passing fast ions, at different fast-ion densities, versus the linear growth rate of the mode. We observe that, in the low growth rate limit, the amplitude values reached in the co-passing ion cases are larger than those in the counter-passing cases, and the scaling with the growth rate is weaker in the former than in the latter cases (the amplitude ratio then reduces with increasing γ). In the large growth rate limit, the amplitude values converge towards the same values and to the same weaker γ dependence.

V. HEURISTIC MODEL

We can resort to a simplified model to interpret the results presented in Fig. 19. We have seen that the basic saturation mechanism is resonant-particle density distortion around the resonance radius (cf. Figure 17), which is conventionally indicated here as density flattening. The radial extension of the region involved in this process is of the same order of that of the structures formed in the \( (P_\phi, \Theta) \) plane (cf. the Appendix and Fig. 21 therein). Such extension can be
evaluated by describing particle orbits in the corresponding $(r, \Theta)$ plane with the following nonlinear pendulum system:

$$\frac{dx}{dt} = -A \frac{S}{|S|} \sin \Theta,$$
\hspace{1cm} (12)

$$\frac{d\Theta}{dt} = Sx.$$ \hspace{1cm} (13)

Here, $x \equiv r - r_{res}$ is the radial distance from the resonant surface (where $d\Theta/dt = 0$), $A > 0$ is proportional to the mode amplitude (responsible for the radial drift, Eq. (12)), and $S$ is related to the radial slope of the resonance frequency (cf. the blue curve in Fig. 11): $\omega_{res} \simeq \omega - S(r - r_{res})$, which is responsible for the wave-particle phase change in Eq. (13). Let us first assume that the growth rate of the mode is sufficiently small that we may treat the mode amplitude as a constant. We can evaluate the radial extension of the closed orbit structure by the radial width of the separatrix between closed and drifting orbits. To this aim, we note that the quantity

$$E(x, \Theta) \equiv \frac{1}{2} \left( \frac{d\Theta}{dt} \right)^2 - A |S| \cos \Theta = \frac{1}{2} (Sx)^2 - A |S| \cos \Theta$$
\hspace{1cm} (14)

is a constant of motion. The separatrix crosses the axis $x = 0$ at $\Theta = \pi$. Then, it is characterised by an $E$ value

$$E_{sep} \equiv E(0, \pi) = A |S|. \hspace{1cm} (15)$$

We can then compute its half width $x_{sep}$ from the condition

$$E(x_{sep}, 0) = E_{sep}, \hspace{1cm} (16)$$

that is

$$\frac{1}{2} (Sx_{sep})^2 - A |S| = A |S|; \hspace{1cm} (17)$$

from which

$$|x_{sep}| = 2 \left( \frac{A}{|S|} \right)^{1/2}. \hspace{1cm} (18)$$

Identifying the radial width of the density flattening region with the full width of the separatrix,

$$\Delta r_{flat} \simeq 2 |x_{sep}|, \hspace{1cm} (19)$$

we can assume that saturation occurs when

$$\Delta r_{flat} \simeq \min[\Delta r_{mode}, \Delta r_{res}]. \hspace{1cm} (20)$$
i.e., the minimum between mode and resonance width. Consistent with the linearisation of $\omega_{\text{res}}$ around $r_{\text{res}}$, $\Delta r_{\text{res}}$ can be evaluated as

$$\Delta r_{\text{res}} \simeq 2 \frac{\gamma}{|K|}. \quad (21)$$

Let us now refer to the two different cases shown in Fig. 12 and adopt the superscripts “+” for the co-passing ion case, “−” for the counter-passing ion one. Let us also neglect the differences between the two cases in terms of mode structure and growth rate; we will focus on the different radial dependence of resonance frequencies (that is, on the different slopes $S^+$ and $S^−$). From Fig. 18, we see that saturation conditions can be written, respectively, as

$$\Delta r_{\text{flat}}^+ \simeq \Delta r_{\text{mode}} \quad (22)$$

or

$$A^+ = \frac{1}{16} |S^+| |\Delta r_{\text{mode}}|^2 \quad (23)$$

and

$$\Delta r_{\text{flat}}^- \simeq \Delta r_{\text{res}}^- \quad \text{for low } \gamma, \quad (24)$$

$$\Delta r_{\text{flat}}^- \simeq \Delta r_{\text{mode}} \quad \text{for large } \gamma \quad (25)$$

or

$$A^- = \frac{1}{16} \frac{\gamma^2}{|S^-|} \quad \text{for low } \gamma, \quad (26)$$

$$A^- = \frac{1}{16} \frac{\gamma^2}{|S^-|} |\Delta r_{\text{mode}}|^2 \quad \text{for large } \gamma. \quad (27)$$

Following Refs. 19 and 20, we call “radial decoupling” the saturation mechanism in the co-passing ion case, as well as in the large-$\gamma$ limit for counter-passing ions, and “resonance detuning” that in the low-$\gamma$ counter-passing case. It can be seen that even this simple model is able to capture the quadratic $\gamma$ scaling observed in the resonance detuning regime, and the weaker dependence typical of the radial decoupling one; it fails, however in justifying the linear character of such weaker dependence.

We can improve the model by taking into account that treating the mode amplitude $A$ as a constant, while evaluating its effect on the density flattening, is appropriate only in the very low growth rate limit: $\gamma T_{\text{orb}} \ll 1$, with $T_{\text{orb}}$ being the time needed for a particle to complete its closed orbit. Let us introduce the equations for the time evolution of $A$ in the following form:

$$\frac{dA}{dt} = \bar{\gamma} A \quad (28)$$

with

$$\bar{\gamma} = \gamma \left(1 - \frac{\Delta r_{\text{flat}}}{\min(\Delta r_{\text{mode}}, \Delta r_{\text{res}})}\right). \quad (29)$$

The above equations have been implicitly used, in the previous derivation, defining the saturation condition as $\bar{\gamma} = 0$ and assuming the flattening region width given in Eq. (19). For a given (static) amplitude $A$, $T_{\text{orb}}$ is an increasing function of $\Theta_0 \in [0, \pi[$, where $\Theta_0$ is the value of $\Theta$ at which the orbit crosses the axis $x = 0$

$$T_{\text{orb}}(\Theta_0) = \frac{4}{(|S|A)^{1/2}} K\left(\frac{\sin^2 \Theta_0}{2}\right), \quad (30)$$

with $K$ being the elliptic integral of the first kind. Then, deeply wave-trapped particles ($\Theta_0 \to 0$) will be characterised by a smaller $T_{\text{orb}}$ than particles close to the separatrix ($\Theta_0 \to \pi$). We can then modify the estimate of $\Delta r_{\text{flat}}$ given in Eq. (19) by assuming that the density flattening involves, at a certain time, only a fraction of the whole region contained within the virtual separatrix that would correspond, in a static limit, to the actual instantaneous amplitude. We write this condition in the form

$$\Delta r_{\text{flat}} \simeq 2|x_{\text{max}}|, \quad (31)$$

where $|x_{\text{max}}|$ is the largest radial excursion observed, at the considered time, among all the wave-trapped particles. We can estimate $x_{\text{max}}$ by the following ansatz:

$$x_{\text{max}} \propto \frac{x_{\text{sep}}}{\gamma T_{\text{orb}}}, \quad (32)$$

with $x_{\text{sep}}$ given, in terms of the actual field amplitude, in Eq. (18) and

$$T_{\text{orb}}^{\text{res}} \equiv \lim_{\Theta_{0} \to 0} T_{\text{orb}}(\Theta_{0}) = \frac{2\pi}{(|S|A)^{1/2}}. \quad (33)$$

We then obtain

$$\Delta r_{\text{flat}} \simeq \frac{A}{x_{\text{flat}}} \quad (34)$$

with $x_{\text{flat}}$ being a proportionality constant. The ansatz is justified a posteriori by numerically solving the system given in Eqs. (12), (13), (28), (29), and (34). Figure 20 compares the time evolution of $\Delta r_{\text{flat}}$, as defined in Eq. (31), with that yielded in Eq. (34) (with $x = 0.5$). The agreement between the two quantities is fairly good. Combining Eqs. (29) and (34), we get

$$\bar{\gamma} = \gamma \left(1 - \frac{A}{x_{\text{flat}}} \frac{1}{\min(\Delta r_{\text{mode}}, \Delta r_{\text{res}})}\right). \quad (35)$$

For $\Delta r_{\text{res}} < \Delta r_{\text{mode}}$, from Eq. (21) we get, for the saturation amplitude ($\bar{\gamma} = 0$)

$$A = \alpha \Delta r_{\text{res}} \gamma, \quad \text{with } \Delta r_{\text{res}} = 2\gamma/|S|, \quad (36)$$

analogous to Eq. (26). For $\Delta r_{\text{mode}} < \Delta r_{\text{res}}$, we find

$$A = \alpha \Delta r_{\text{mode}} \gamma, \quad \text{with } \Delta r_{\text{mode}} = \text{const.} \quad (37)$$

The predictions of this second qualitative model are consistent with the scalings shown in Fig. 19 and improve the previous ones (Eqs. (23) and (27)) for radial decoupling. In particular, we see that the linear dependence on $\gamma$ is
VI. SUMMARY AND CONCLUSIONS

In this paper, linear and nonlinear dynamics of $n = 2$ BAEs driven unstable by anisotropic fast-ion populations (co-passing or counter-passing ions) have been investigated by single toroidal number numerical simulations performed by the hybrid MHD-particle code XHMGC. The linear-dynamics mode properties appear very similar for co-passing and counter-passing ion drive, with respect to radial structure, frequency, and growth rate (slightly larger for counter-passing ions). On the other hand, the nonlinear dynamics exhibit significant differences: namely, saturation mode amplitude is larger, in the reference simulation considered, for the (slightly weaker) co-passing ion case. Furthermore, the scaling of such amplitude with the mode growth rate is linear, different from the quadratic scaling obtained, in the low growth rate limit, in the counter-passing ion case. These differences can be explained on the basis of the different radial profile of the resonance frequency in the two cases: flat, for co-passing ions; steep, for counter-passing ions. Indeed, the radial region where the resonant interaction can take place is set by nonvanishing mode amplitude and matched resonance condition, $|\omega - \omega_{res}| \leq \gamma$. Each of these conditions is verified within a characteristic radial interval. Two regimes can be distinguished, depending on the relative size of the two intervals, $\Delta r_{mode}$ and $\Delta r_{res}$. In the first regime, the most stringent condition is given by the frequency matching ($\Delta r_{res} < \Delta r_{mode}$); in the second regime, by the mode strength ($\Delta r_{mode} < \Delta r_{res}$). The different radial dependence of $\omega_{res}$ for co-passing and counter-passing ions yields, for a given growth rate, $\Delta r_{res} < \Delta r_{res}^+$ (at the same time, $\Delta r_{mode}$ is very similar for the two fast-ion distributions). In fact, in the reference case and, more generally, in the low growth rate limit, $\Delta r_{res}^+ < \Delta r_{mode} < \Delta r_{res}^-$. In such limit, saturation, which is reached when the resonant-particle density flattening extends over the whole resonant-interaction width, corresponds to a flattening with of the order of the mode width, for co-passing ions; of the resonance width, for counter-passing ions. It has been shown that this difference in the saturation processes (called, respectively, radial decoupling and resonance detuning) accounts for the different saturation amplitude and its different scaling (linear vs quadratic) with increasing growth rate. For larger growth rates, even the resonance width for counter-passing ions becomes larger than the mode width, and a transition to the radial decoupling regime and the corresponding linear scaling is observed for the modes driven by such ions; saturation amplitudes tend to the same values for the two cases.

Note that the analysis presented in this paper does not encompass several aspects of Alfvén mode nonlinear dynamics, able to play an important role for different equilibria, like frequency chirping, large nonlinear modification of mode structure, and synergic interaction of different toroidal number modes.

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APPENDIX: HAMILTONIAN MAPPING TECHNIQUES

In this appendix, we briefly recall some elements of the Hamiltonian mapping approach to the analysis of the nonlinear mode-particle dynamics. The selection of a suited test-
particle sample has been described in Sec. III B. Following Ref. 19, we can represent such sample in the plane \((\Theta, P_\phi)\), with \(\Theta \equiv \omega t + m\theta - n\phi\) being the wave-particle phase mapped into the interval \([0, 2\pi]\) (Fig. 21). At each time, each marker corresponds to the last equatorial-plane crossing \((\theta = 2\pi j\), with \(j\) being an integer number) of a certain test particle; the marker changes positions, if needed, only after a new poloidal orbit has been completed. Each marker is doubled by a twin marker in the phase interval \([2\pi, 4\pi]\) in order to give a better visualisation of its dynamics. Marker colours (red or blue) depend on the initial \(P_\phi\) value of each test particle and do not change with time. The boundary between two colours is initially fixed at \(P_\phi = P_{\phi, res}\) (corresponding to \(r_{res}\), that is the position where \(\omega_{res} = \omega\) and the wave phase \(\Theta\) is a constant). During the whole linear phase, in which the field amplitude is so small that its effects on the particle orbits are negligible, \(P_\phi\) is almost conserved. Then, during such phase (Fig. 21(a)), particle trajectories in the \((\Theta, P_\phi)\) plane essentially reduce to fixed points for \(P_\phi = P_{\phi, res}\), while they correspond to drift along the \(\Theta\) axis in the positive/negative direction, for \(P_\phi\) greater/less than \(P_{\phi, res}\). In the nonlinear phase, \(P_\phi\) varies because of the mode-particle interaction (e.g., radial \(E \times B\) drift). Even particles that were initially resonant are brought out of resonance, getting nonzero \(d\Theta/dt\) and drifting in phase until the drift in \(P_\phi\) is inverted. Particles that cross the \(P_\phi = P_{\phi, res}\) line revert values of \(d\Theta/dt\) as well. Thus, their orbits are bounded and they would properly close if the field amplitude were constant in time. This is true for particles born close to the resonance, while particles born with \(P_\phi\) far from the resonance maintain drifting orbits, as they do not cross \(P_\phi = P_{\phi, res}\). Bounded orbits and drifting orbits are divided by an instantaneous separatrix, whose \(P_\phi\) width increases with increasing field amplitude (Fig. 21(b)).

![FIG. 21](image_url) Representative of the whole test-particle sample in the plane \((\Theta, P_\phi)\), at certain times in the linear (a) and nonlinear (b) phase. The position of each marker corresponds to the last equatorial-plane crossing of a test particle. Colours (red or blue) depend on the initial \(P_\phi\) value of each test particle and do not change with time. The boundary between two colours is initially fixed at \(P_\phi = P_{\phi, res}\), corresponding to \(r_{res}\), to the position where \(\omega_{res} = \omega\) and the wave phase \(\Theta\) is a constant). During the whole linear phase, in which the field amplitude is so small that its effects on the particle orbits are negligible, \(P_\phi\) is almost conserved. Then, during such phase (Fig. 21(a)), particle trajectories in the \((\Theta, P_\phi)\) plane essentially reduce to fixed points for \(P_\phi = P_{\phi, res}\), while they correspond to drift along the \(\Theta\) axis in the positive/negative direction, for \(P_\phi\) greater/less than \(P_{\phi, res}\). In the nonlinear phase, \(P_\phi\) varies because of the mode-particle interaction (e.g., radial \(E \times B\) drift). Even particles that were initially resonant are brought out of resonance, getting nonzero \(d\Theta/dt\) and drifting in phase until the drift in \(P_\phi\) is inverted. Particles that cross the \(P_\phi = P_{\phi, res}\) line revert values of \(d\Theta/dt\) as well. Thus, their orbits are bounded and they would properly close if the field amplitude were constant in time. This is true for particles born close to the resonance, while particles born with \(P_\phi\) far from the resonance maintain drifting orbits, as they do not cross \(P_\phi = P_{\phi, res}\). Bound orbits and drifting orbits are divided by an instantaneous separatrix, whose \(P_\phi\) width increases with increasing field amplitude (Fig. 21(b)).
