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Source Regulation of Fast Energetic Particle Driven Alfvén Modes Dynamics

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In a previous paper [1] we have shown, on the basis of particle simulations performed by the HMGC code, that saturation of Alfvén modes driven unstable by fusion-produced alpha particles (hereafter indicated with α) can induce a broadening of the α pressure profile in some of the proposed ITER scenarios. The validity limit of these results is mainly due to the absence of fast-ion sources in the underlying model and to the fact that it does not address the dynamics of a plasma discharge on transport time scales. The stability of a given scenario is then analyzed by *assuming* the reference equilibrium, i.e. without considering how its formation is affected by the Alfvén-mode dynamics itself. A proper multiple-time-scale approach would describe the evolution of a succession of quasi-equilibria characterized by increasing values of the α pressure gradient. The fast Alfvén-mode dynamics affecting each quasi-equilibrium could distort the α distribution function in such a way to modify the next quasi-equilibrium dynamics. The final scenario configuration, reached in this way, could then differ from that obtained in Ref. [1], possibly with milder effects on the α redistribution and transport. In this paper we try to address this point, by simulating the building up of the β_H radial profile, with β_H being the ratio between α and magnetic pressures. To this aim, we add a source term to the Vlasov equation ($dF/dt = S$), chosen in such a way that, in the absence of nonlinear effects, the distribution function would be given by $F(t,Z) = \nu(t)F_{\rm eq}(Z)$, with Z representing the set of relevant phase-space coordinates and $F_{\rm eq}$ being the equilibrium distribution function related to the initial conditions: we will then set $S(t,Z) = (d\nu/dt)F_{\rm eq}(Z)$. For these *source simulations*, we switch the source term on only in the time interval $t_{\rm on} < t < t_{\rm off}$, with ν varying linearly, in that interval, from $\nu = 1$ to $\nu = \beta_{H0}^{\rm fin}/\beta_{H0}^{\rm in}$, and being constant outside. Here, $\beta_{H0}^{\rm in}$ is the initial on-axis β_H value and $\beta_{H0}^{\rm fin}$ is the corresponding nominal final value. Note that, if the Alfvén mode dynamics were retained only for $t > t_{\rm off}$, we would recover exactly the same results obtained in a simulation performed without a source term (hereafter, a *no-source simulation*), with $\beta_{H0}|_{t=0} = \beta_{H0}^{\rm fin}$. Specific aim of this work is then investigating whether important modifications of the final saturated state can instead occur when the Alfvén dynamics is retained during all the phases of the simulation. We will consider only the reversed-shear SC4 ITER scenario:

this scenario was indeed shown, in Ref. [1], to be the most prone to losses, in the sense that even a moderate increase in the assumed energetic-particle energy content could significantly enhance the α transport. To be consistent with the quoted reference, we neglect the nonlinear mode-mode coupling among different toroidal mode numbers, limiting the analysis to the evolution of the most unstable toroidal mode ($n = 2$, in this case). However, neglecting these nonlinear wave-wave interactions prevents the saturation of unstable tearing modes. This fact sets a limit to the longest time scale we are able to simulate. We will then extrapolate our conclusions on the real – very long – transport-time-scale system behavior from the investigation of much shorter time-scale numerical simulation results.

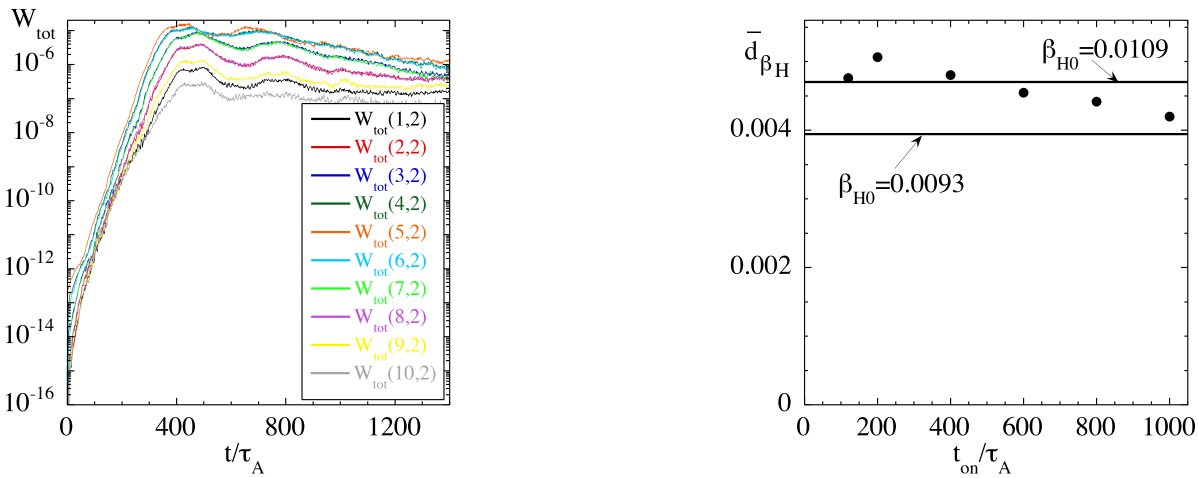

Figure 1: Time evolution of the different poloidal harmonics fluctuating energy $W_{tot}(m,n)$ for a no-source simulation with $\beta_{H0} = 0.0093$ (*left*). Broadening of the β_H profile, after saturation has been reached, for source simulations with $\beta_{H0}^{\text{in}} = 0.0093$, $\beta_{H0}^{\text{fin}} = 0.0109$ and different values of t_{on} (*right*); values related to no-source simulations are also reported.

We start considering two no-source simulations, corresponding to $\beta_{H0} = 0.0093$ and $\beta_{H0} = 0.0109$, respectively. Both cases have been found, in Ref. [1], unstable with respect to shear-Alfvén modes located around the maximum-drive magnetic surface. The former, however, which corresponds to the nominal scenario value, exhibits a relatively little nonlinear broadening of the α pressure profile, while the latter shows a slightly larger radial particle redistribution. In order to check whether a dynamical approach to the equilibrium can regulate such nonlinear effects, we compare the results obtained in these two cases with those obtained by few source simulations characterized by $\beta_{H0}^{\text{in}} = 0.0093$, $\beta_{H0}^{\text{fin}} = 0.0109$, $t_{\text{off}} - t_{\text{on}} = 100\,\tau_A$ (with τ_A being the Alfvén time) and different values of t_{on}. In Fig. 1 *left*, the time evolution of the different poloidal harmonics fluctuating energy is reported for the lower-β_{H0} no-source simulation, while Fig. 1 *right* shows, for each source simulation, the asymptotic value, $\bar{d}_{\beta_H}$, of the quantity $d_{\beta_H}(t) = \frac{1}{a^2}\int_0^a dr\ r\left|\frac{\beta_H(r,t)}{\nu(t)\beta_H^{eq}(0)} - \frac{\beta_H^{eq}(r)}{\beta_H^{eq}(0)}\right|$, which represents a measure of the nonlinear broadening of the α pressure profile. Such values are compared with those obtained in the lower and higher-β_{H0} no-source simulations. We observe that, in spite of the fact that the overall energy content is the same for each case, the deviation of the pressure profile from the equilibrium one depends on the switching time $t_{\rm on}$. More precisely, if the source term acts on the system during the phase of linear growth of the Alfvén modes, the nonlinear broadening is very close to that observed in the higher-β_{H0} no-source case. As $t_{\rm on}$ is increased, making the source term progressively acting on a configuration more deeply affected by the nonlinear Alfvén mode dynamics, the increase of free-energy content is less capable to produce a similar broadening. An almost complete suppression of the further impact on the pressure profile is obtained if the system has time enough to complete its original saturation dynamics ($t_{\rm on} \approx 1000\tau_A$).

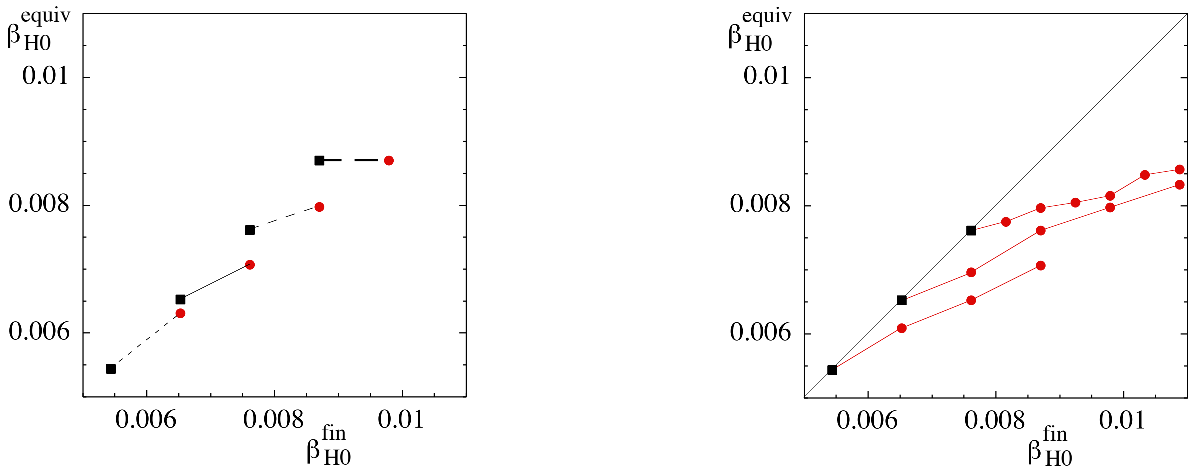

Figure 2: Equivalent-distortion β_{H0} versus $\beta_{H0}^{\rm fin}$, for different source simulations: fast after-saturation ramps, with fixed β_{H0} increment and various values of $\beta_{H0}^{\rm in}$ (*left*); slow ramps with different values of $\beta_{H0}^{\rm in}$ and $\beta_{H0}^{\rm fin}$ (*right*).

If this suppression has to be ascribed to the capability of the original – lower-β_{H0} – nonlinear dynamics in modifying the α distribution function in such a way to reduce the reactivity of the system to the α-pressure increase, we expect it should be less evident if the starting configuration is characterized by a lower energy content (and, hence, a weaker nonlinear dynamics). Such expectation is indeed fulfilled by the results we found from source simulations, analogous to the regulating one (large $t_{\rm on}$) discussed with reference to Fig. 1, but with different values of $\beta_{H0}^{\rm in}$. For each case we evaluate the quantity $\beta_{H0}^{\rm equiv}$, defined as the value of $\beta_{H0}|_{t=0}$ that would yield the same distortion of the pressure profile in a no-source simulation; in Fig. 2 *left*, we plot these values versus $\beta_{H0}^{\rm fin}$ (red circles): a regulating effect of the nonlinear Alfvén dynamics yields, for a given simulation, $\beta_{H0}^{\rm equiv} < \beta_{H0}^{\rm fin}$. In order to make this effect more apparent, for each case, the point corresponding to the no-source simulations characterized by $\beta_{H0}|_{t=0} = \beta_{H0}^{\text{in}}$ has also been plotted (black square) and connected with the source-simulation result; note that, for a no-source simulation, $\beta_{H0}^{\text{equiv}} \equiv \beta_{H0}^{\text{fin}} \equiv \beta_{H0}^{\text{in}}$. It can be seen that the regulation is absent for the low β_{H0}^{in} case, and it becomes progressively more significant as this parameter is increased. When β_{H0}^{in} exceeds a certain value ($\beta_{H0}^{\text{in}} \gtrsim 0.0085$, in this case), the saturation dynamics fully prevents the system from developing any further broadening when the α pressure is increased.

This transition from non-suppressing to fully-suppressing Alfvén mode dynamics with respect to further α redistributions suggests that, in a realistic – very slow – approach to the scenario α pressure profile, an adiabatic regulation, able to prevent *ab initio* any profile broadening, should not be observed. We indeed expect that a certain broadening level will be reached, while the pressure content increases. The broadening process will then slow down, as the Alfvén wave suppressing dynamics becomes more effective; eventually, such a process will completely stop, yielding an upper limit in the overall nonlinear profile deformation. At that point, further increasing the α pressure should not cause a worsening of its radial profile stability, unless additional nonlinear dynamics sets in. To test these tentative conclusions, we perform a different type of simulations: quite long density ramps ($t_{\text{off}} - t_{\text{on}} = 2000\tau_A$), starting immediately ($t_{\text{on}} = 0$), with different values of β_{H0}^{in} and β_{H0}^{fin}. These simulations are the best possible approximations of the realistic long-time approach to equilibrium, compatibly with two competing problems: the existence of intrinsic model limitations, which prevent us – as explained – from adequately prolonging the pressure ramps, and the need of keeping the rate of pressure increase realistically low, which limits the $\beta_{H0}^{\text{fin}} - \beta_{H0}^{\text{in}}$ increment that can be covered by each ramp. We have then to recover the salient information by looking at a few sets of simulations, each characterized by a different value of β_{H0}^{in} and a relatively narrow range of β_{H0}^{fin} values. The results are reported in Fig. 2 *right*, with the same definitions described for Fig. 2 *left*. Cases related to the same value of β_{H0}^{in} are connected for the sake of legibility. We see that a $\beta_{H0}^{\text{equiv}}$ saturation clearly emerges at $\beta_{H0} \approx 0.0085$, consistently with the results discussed above. We can conclude that, in a real case, even if the final equilibrium corresponded to a larger value of β_{H0}, the overall nonlinear broadening of the α pressure profile should not exceed the amount found by a no-source simulation characterized by the asymptotic saturated $\beta_{H0}^{\text{equiv}}$ value, provided the systems remains sufficiently close to marginal stability.

References

[1] Vlad G., Briguglio S., Fogaccia G., Zonca F. and Schneider M. 2004, Paper IAEA-CSP-25/CD/IT/P3-31, presented at the 20th IAEA FEC, Nov. 1-6 2004, Vilamoura, Portugal.