Alfvén eigenmode driven by alpha particles and NBI energetic particles

L. García[1], J. Varela[2], D.A. Spong[2] and Y. Todo[3]

[1] *Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain*

[2] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

[3] *National Institute for Fusion Science, Toki, Gifu, 509-5292, Japan*

Introduction

Energetic particle (EP) driven instabilities can enhance the transport of fusion produced alpha particles, energetic neutral beams and particles heated using ion cyclotron resonance heating (ICRF). The consequence is decreased heating efficiency in devices as present tokamaks and stellarators.

Alfvén eigenmodes (AE) are driven in the spectral gaps of the shear Alfvén continua, destabilized by super-Alfvénic alpha particles and energetic particles. The destabilizing effect of combined EP species populations has not been extensively studied. In future nuclear fusion devices such as ITER, different EP species will coexist in the plasma, in particular NBI ions and alpha particles, so it is desirable to analyze the AE stability in these conditions. In present fusion devices the effect of AEs destabilized by alphas is absent although the combination of different NBI EP species populations could lead to similar damping effects.

Here, we analyze the AE linear stability of ITER plasmas, identifying the configurations with damping on the dominant AE caused by multiple EP species effects. If the AEs growth rate of the multiple EP species case (NBI EP + alpha particles) is smaller compared to the AEs destabilized individually by the NBI driven EP and alpha particles, we consider that a multiple EP species damping is taking place. In addition, we study the effect of the NBI EP and alpha particles β, energy and density profile on the AEs growth rate and frequency.

The study also includes LHD experiments dedicated to analyze the destabilization of AE by NBI energetic particles, easily excited in configurations with low magnetic field ($B_0 = 0.5$ T) and bulk density ($n_0 = 5.8 \times 10^{18}\,\mathrm{m}^{-3}$). In this LHD configuration the plasma is heated by neutral beams injecting energetic hydrogen neutrals tangentially using three NBI lines up to 180 keV, destabilizing $n = 1$ and $n = 2$ Toroidal Alfvén eigenmodes (TAE).

Model

The model used in the simulations described here includes a set of reduced MHD equations and the moment equations of the NBI driven energetic ion and alpha particles density and parallel velocity. The set of reduced equations consists of four evolution equations for the magnetic poloidal flux ψ, the toroidal component of the vorticity U, the pressure p and the parallel velocity $v_{\parallel th}$ of the thermal plasma. The effect of the energetic particle populations is included in the formulation as moments of the kinetic equation truncated with a closure relation [1]. These describe the evolution of the energetic particle density (n_f) and velocity moments parallel to the magnetic field lines ($v_{\parallel f}$) for each driven EP species. Operators are constructed to model the averaged drift velocity of a passing particle and its diamagnetic drift frequency. The coefficients of the closure relation are selected to match a two-pole approximation of the plasma dispersion function. Interested readers are referred to [2] for more details about the model.

The FAR3d code follows the evolution of the field variables, starting from an equilibrium calculated by the VMEC code and transformed to Boozer coordinates. The FAR3d code uses finite differences in the radial direction and Fourier expansions in the two angular variables. The numerical scheme is semi-implicit in the linear terms.

ITER reversed shear configuration

In the case of ITER, we consider two energetic particle sources: neutral beam injection (NBI) and alpha particles. Fig. 1 shows the AE growth rate γ (*a*), and frequency f (*b*), if we include in the model only the NBI driven EP (blue triangles), only alpha particles (red dots), NBI + alpha particles (black squares) and NBI + alpha particles adding the FLR and electron- ion Landau damping effects (gray stars). The growth rate is normalized to the inverse Alfvén time $\tau_A^{-1} = v_{A0}/R_0$, where v_{A0} is the Alfvén speed at the magnetic axis, and R_0 is the major radius. The growth rate of the NBI + alpha simulations is lower compared to the single NBI or single alpha particles simulations, so a multiple EP damping effects exist although it is not large enough to stabilize the AEs. The modes $n < 11$ are AE stable. The AEs growth rate increases with the toroidal mode number although the profile slope decays for $n > 32$. The AEs frequency shows the same tendencies as the growth rate.

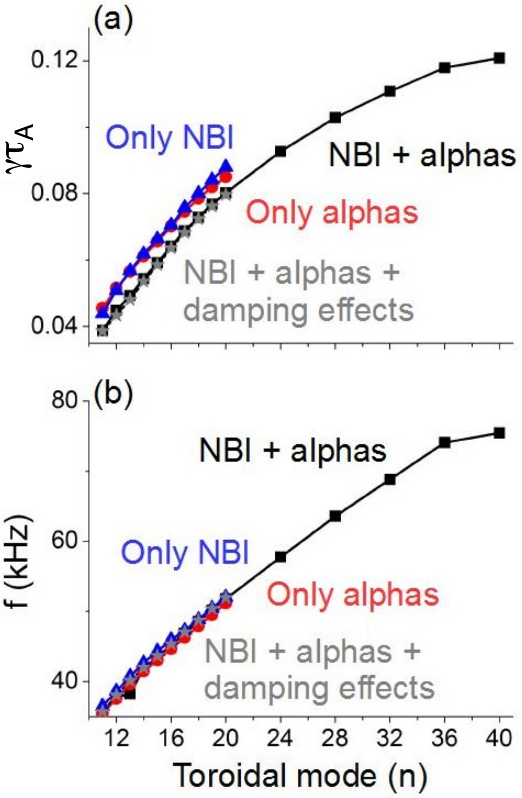

Figure 1: AEs growth rate (a) and frequency (b) in the simulations with only NBI driven EP (blue triangles), only alpha particles (red dots), NBI + alpha particles (black squares).

The second part of the study consists in analyzing the effect of β and energy (controlled by the ratio $v_{th,f}/v_{A0}$) of the NBI driven EP and alpha particles on the AEs growth rate an frequency. Here, $v_{th,f} = \sqrt{T_f/M_f}$.

First we study the effect of the alpha particles β_α and energy when the NBI driven EP configuration is fixed. Fig. 2 shows AE growth rate for different β_α and energies. An increase of β_α leads to a slightly drop of the growth rate except for the $n < 14$ AEs if $\beta_\alpha = 0.015$. The TAE lowest growth rate is observed when $v_{th,\alpha}/v_{A0} = 0.6$.

Next we study the effect of the NBI driven EP β_f, energy and EP density profile on the AEs growth rate and frequency if the alpha particle configuration is fixed. An increase of β_f leads to a slightly drop of the AE growth rate except for $n < 16$ AEs if $\beta_f = 0.015$ where AEs with a higher growth rate are destabilized. The TAEs lowest growth rate is observed for $v_{th,f}/v_{A0} = 0.2$ and a $n = 11$ AE with a larger growth rate is destabilized if $v_{th,f}/v_{A0} = 0.4$.

If we modify the location of the NBI driven EP density profile gradient and the flatness, there is a small decrease of the AEs growth rate if the NBI is deposited off axis although the growth rate variation is negligible if the density profile flatness changes, pointing out that the leading destabilization effect is caused by the alpha particles.

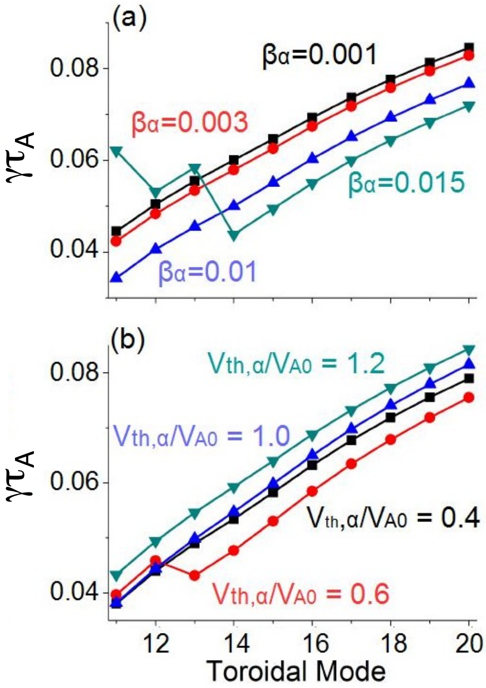

Figure 2: AEs growth rate for different β_α (a) and $v_{th,\alpha}/v_A$ (b) values.

In summary, the alpha particles perturbation is dominant, except if the NBI driven EP β_f is large enough to overcome the alpha particle destabilization. Furthermore, the NBI driven EP hold a damping effect over the AEs destabilized by the alpha particles, showing a lower growth rate compared to the simulations with only NBI driven EP and only alpha particles, although the damping effect is not large enough to stabilize the AEs.

Multiple NBI lines in LHD low density and magnetic field discharges

In this case, the sources are two neutral beam injectors with different injection energies. For both injectors, the EP energy is considered constant, with no radial variation. For one of the injectors (A) the NBI EP density profile is fixed. For the second injector (B), we consider different EP density profiles proportional to $1 + \tanh[\text{Adens}(\text{Bdens} - \rho)]$. Adens controls the the gradient and Bdens controls the location of the gradient maximum.

Fig. 3 shows the $n = 1$ and $n = 2$ AE growth rate and frequency when the variable NBI driven EP density profile is modified (variable NBI $T_{b0} = 48$ keV and $\beta_f = 0.0212$). Multiple NBI damping effects stabilize the $n = 1$ AE if Bdens > 0.5 or Adens < 0.5. On the other hand, the $n = 2$ AE is not stabilized although a weak damping effect is observed if Adens < 0.1. The AEs growth rates decrease in the multiple and single NBI B simulations if Bdens increases, so an on-axis NBI deposition leads to the most unstable configurations. The AEs frequencies decrease if the variable NBI is deposited off-axis, except for the $n = 2$ AE showing a local minimum if Bdens $= 0.4$, increasing between $0.5 <$ Bdens < 0.6. In addition, the AE $n = 1$ ($n = 2$) frequency increases (decreases) as the variable NBI driven EP profile is flattened, except if Adens < 1 (Adens < 0.5).

The AEs growth rates and frequencies trends in the simulations with helical couplings included are similar to the simulations without helical couplings, although the $n = 1, 9, 11$ AE growth rate and frequency are higher for all Adens and Bdens values. On the other hand, $n = 2, 8, 12$ AE growth rate and frequency are smaller in all simulations. Therefore, $n = 1, 9, 11$ ($n = 2, 8, 12$) AEs are less (more) sensitive to the multiple NBI damping effect. It should be noted that the $n = 2, 8, 12$ AEs as well as the $n = 1, 9, 11$ AEs are stable in the multiple NBI simulations if the variable NBI driven EP density profile is flat enough compared to the fixed NBI (Adens < 0.1).

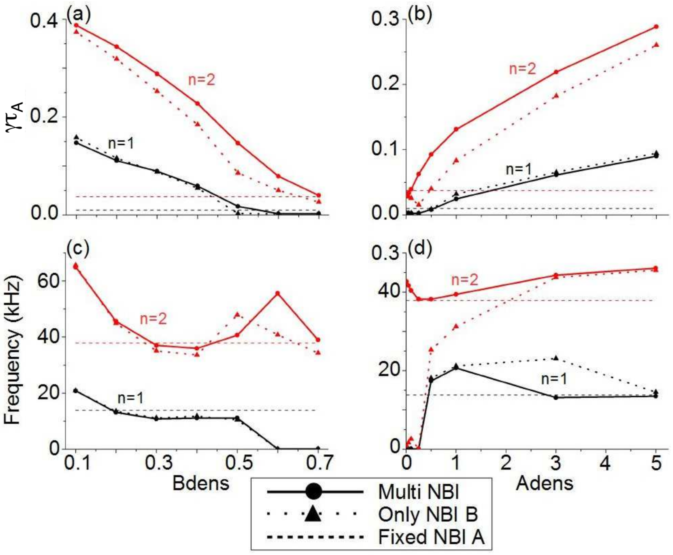

Figure 3: AE growth rate (a) and frequency (c) vs Bdens. AE growth rate (b) and frequency (d) vs Adens. Solid lines show the multiple NBI simulations, dotted lines the single variable NBI B simulations and dashed lines the single fixed NBI A simulations.

References

[1] D.A. Spong, B.A. Carreras and C.L. Hedrick, *Phys. Plasmas B* **4**, 3316 (1992)

[2] J. Varela, D.A. Spong and L. Garcia, *Nucl. Fusion* **57**, 046018 (2017)