Simulations of Alfvén eigenmodes in CFQS

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Introduction

Quasi-axisymmetric (QA) device combines the advantages of both tokamak and stellarator, and thus, it can be considered as a disruption-free tokamak and it excites the interests of the fusion community. Alfvén eigenmode is an important issue for magnetic confinement fusion because it enhances energetic particle (EP) transport and degrades heating performance. The properties of Alfvén eigenmode must be carefully analyzed in order to better understand particle behavior and to predict the confinement level. Nowadays, a QA device named CFQS is being constructed under an international joint program between National Institute for Fusion Science (Japan) and Southwest Jiaotong University (China), and the first plasma will be generated soon[1, 2]. Thus, before the operation, the simulation research of the interaction between EP and Alfvén eigenmode in QA configuration becomes significant and urgent.

Simulation model

The present research is devoted to the simulations of Alfvén eigenmodes in CFQS. The simulation is conducted using MEGA which is a hybrid simulation code for EPs interacting with a magnetohydrodynamic (MHD) fluid[3, 4, 5]. The parameters of plasma including major radius 1 m, magnetic field strength 1 T on magnetic axis, plasma density 1×10^{19} m^{-3}, and plasma beta 1%, are based on Ref.[1, 2]. The equilibria are calculated using HINT code which is a three-dimensional (3D) magnetohydrodynamic (MHD) equilibrium solver[6]. Tow cases with bootstrap currents 20 kA and 5 kA are considered in the present simulations. In the 20 kA bootstrap current case, 6 islands appear on the edge as shown in Fig. 1(a), while in the 5 kA bootstrap current case, the islands disappear and the magnetic field on the edge region becomes stochastic as shown in Fig. 1(b). The rotational transform ι profiles are slightly different because of the existence of islands, as shown in Fig. 1(c). The energy of the neutral beam is 40 keV. The pressure profile of EP is the same as the pressure profile of bulk plasma. A slowing-down distribution of EP is assumed. Also, the EP distribution in pitch angle space is Gaussian type which is almost tangentially counter-injected.

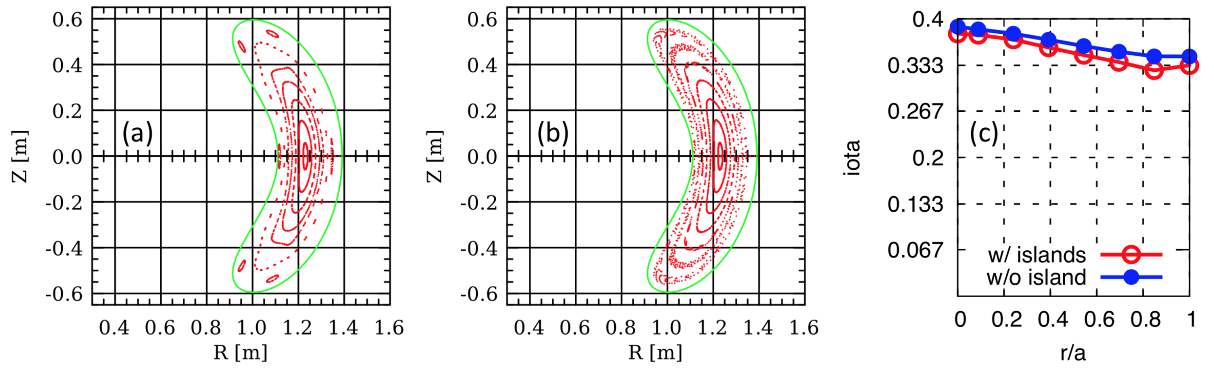

Figure 1: (a) The equilibrium with 6 islands. (b) The equilibrium without island. (c) The rotational transform ι profiles in the above 2 cases.

Simulation results

A global mode with mode number m/n=3/1 is excited under the presence of islands. Some other components $n = n_0 + iN_{fp}$ (n=3 and n=-1) are also strong as shown in Fig. 2(a), where $n_0 = 1$ in the present case, i is an arbitrary integer (i=1, -1), and number of field period $N_{fp} = 2$ for CFQS. Strong mode coupling happens under the condition of very small N_{fp}. This is consistent with the theoretical prediction by D. Spong[7]. Also, the frequencies of different harmonics (m/n=3/1, 5/3, 5/1, 3/3, and 1/-1) are the same, but amplitudes are different. It confirms that these harmonics constitute the same eigenmode. As shown in Fig. 2(b), the mode growth rate increases with EP pressure, it represents that the mode is driven by EP. But the mode frequency does not depend on EP, it implies that the mode may be an eigenmode. The mode frequency of 78 kHz is the same as global Alfvén eigenmode (GAE) frequency $(n - m\iota) \times \omega_A$, where Alfvén frequency $\omega_A = 6.147 \times 10^6$ rad/s, n=1, m=3, and $\iota = 0.36$. Since the simulated mode is an EP driven global eigenmode, and the mode frequency is the same as GAE, finally, this mode is identified as GAE.

With time evolution, GAE frequency chirps down from 78 kHz in linear phase to 70 kHz in nonlinear phase, as shown in Fig. 3(a) and (b). As shown in Fig. 3(c) and (d), the EP energy transfer is negative. This represents the EPs lose energy and the mode obtains energy, and that is the reason why the mode is destabilized. In pitch angle Λ and energy E phase space, the top left corner represents high-frequency region, and the right bottom corner represents low-frequency region. The colorful curves in the figure represent constant frequencies. In the linear phase, the frequency of the resonant region is high, while in the nonlinear phase, the frequency of the resonant region shifts downward, which represents the frequency becomes low. The frequency decreasing process in Fig. 3(c) and (d) and the frequency chirping process in Fig. 3(a) and (b)

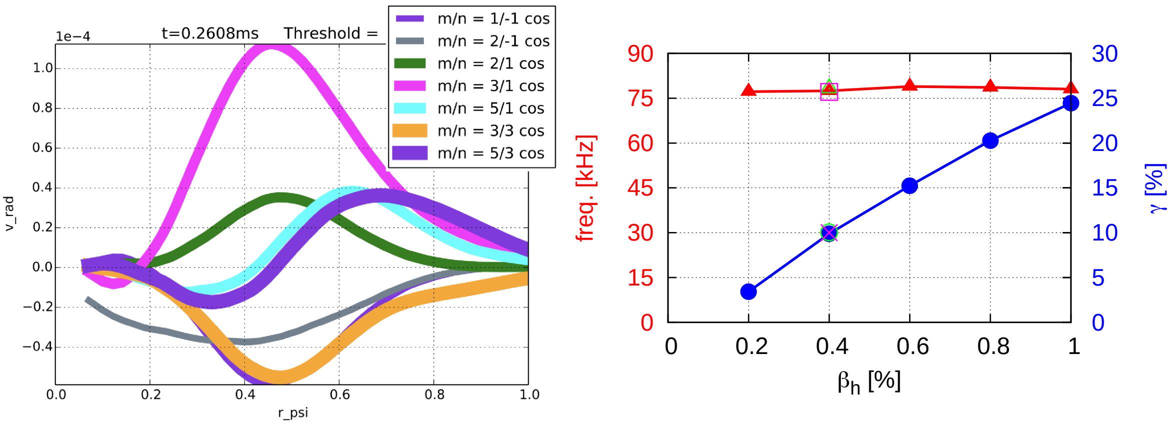

Figure 2: (a) The mode structure in the case with islands. (b) Mode frequencies and growth rates versus EP pressure.

occur simultaneously. In addition to energy transfer, δf distribution of EPs are also plotted in phase space, as shown in Fig. 3(e) and (f). Hole and clump structures (positive and negative δf) are formed. The hole-clump pair moves from high-frequency region to low-frequency region during GAE frequency chirping. This indicates the frequency of particles in the hole-clump also chirps down, and the particles comprising the hole and clump are kept resonant with GAE during the frequency chirping.

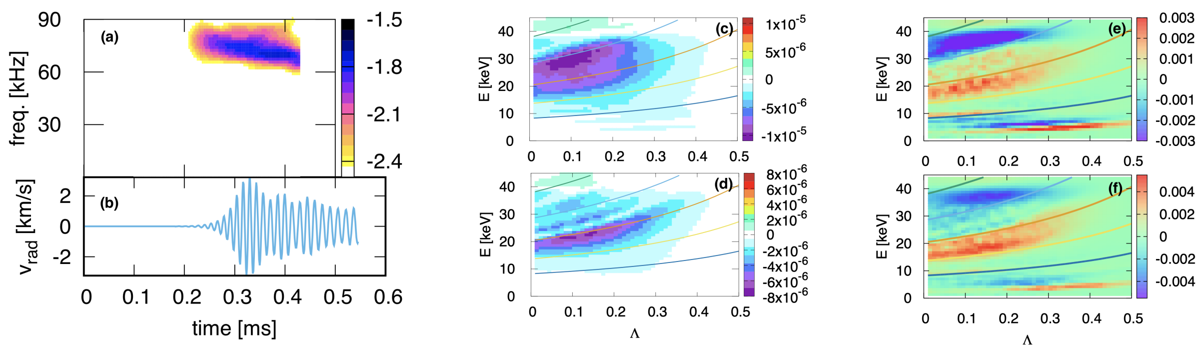

Figure 3: (a) GAE frequency spectrum. (b) Time evolution of GAE mode amplitude. (c) EP energy transfer in (Λ, E) phase space where Λ is pitch angle and E is energy, linear growth stage. (d) EP energy transfer in (Λ, E) phase space, nonlinear saturated stage. (e) EP distribution δf in (Λ, E) phase space, linear growth stage. (f) EP distribution δf in (Λ, E) phase space, nonlinear saturated stage.

Another global mode with mode number m/n=5/2 is also excited without islands. Similar to the GAE case, strong mode coupling happens, and the mode growth rate increases with EP pressure but mode frequency does not depend on EP. The mode frequency of 125 kHz is close to toroidal Alfvén eigenmode (TAE) frequency, and thus, the simulated mode is identified as a TAE. In the saturated phase, the frequency of the dominant branch chirps down, and the frequency of the sub-dominant branch chirps up. The orbit frequency of particles in the hole-clump also chirps down (and up) simultaneously. This indicates that the particles comprising the hole and clump are kept resonant with TAE during the frequency chirping.

Summary

In summary, the simulations of the EP driven instabilities in CFQS are conducted using MEGA code for the first time. GAE and TAE are found in CFQS with and without islands, respectively. The dominant mode numbers are m/n=3/1 and m/n=5/2 for GAE and TAE. Strong mode coupling is found under the condition of very low N_{fp} value. This is consistent with theoretical prediction[7]. In the nonlinear saturated phase, both GAE and TAE frequencies chirp, and hole-clump structures are formed in phase space. The frequency of the hole-clump pair changes simultaneously with mode frequency, and this indicates that the particles comprising the hole and clump are kept resonant with the mode during the frequency chirping.

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