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Hybrid simulation of fishbone instabilities with reversed safety factor profile

Wei Shen[1], G. Y. Fu[2], Feng Wang[3], Liqing Xu[1], Zhenzhen Ren[4]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, China

[2]Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, China

[3]School of Physics, Dalian University of Technology, Dalian 116024, China

[4]School of Physics and Materials Science, Anhui University, Hefei 230039, China

shenwei@ipp.ac.cn

ABSTRACT

- Hybrid simulations of fishbone instabilities with reversed safety factor have been carried out by the global hybrid code M3D-K. There are two types of fishbone considering the reversed q profile: dual resonant fishbone (DRF) with double q=1 surfaces and non-resonant fishbone (NRF) with the minimum value of safety factor q_{min} a little larger than unity.
- Based on EAST-like conditions, linear simulations show that the DRF is excited with splitting radial mode structure due to double q=1 surfaces. DRF transits to NRF when q_{min} increases from below unity to above unity. Nonlinear simulations show that the saturation of the DRF is due to MHD non-linearity while the saturation of the NRF is mainly due to the non-linearity of fast ions.

BACKGROUND

- Energetic particle driven instabilities, such as fishbones and various Alfvén eigenmodes, can induce energetic particle loss, degrade fast particle confinement, and even lead to serious damage of the first wall.
- A non-monotonic safety factor profile with a reversed magnetic shear configuration has been proposed as an advanced scenario for future ITER operation.
- When q_{min} < 1, the fishbone would have dual resonant surfaces, and the mode has been theoretically ananlyzed to have a two-step stucture which is similar to that of double kink modes.
- When q_{min} > 1, the non-resonant fishbones were widely observed in both conventional tokamaks and spherical tokamaks.

Linear simulation results

EQUILIBRIUM PROFILES AND PARAMETERS

Equilibrium profiles and parameters are chosen based on the Shot #48605 of the EAST tokamak with different pressure and safety factor profile. Central total beta including both energetic particles and thermal plasmas is chosen to be 3.52%. The injection energy of beam ions is 60 keV. Trapped fast ions are chosen to be analyzed with pitch angle parameter Λ_0=1.0. Figure 1 shows the profiles of pressure and safety factor

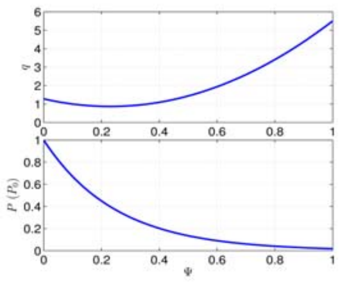

FIG. 1. Equilibrium profiles.

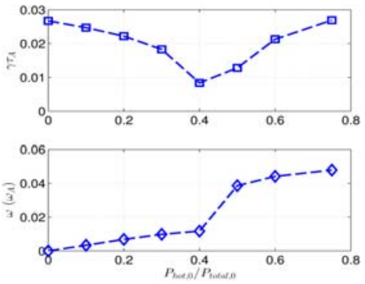

FIG. 2. mode frequency and growth rate vs. pressure fraction.

SIMULATION RESULTS

- ➢ With fixed total pressure, mode frequency and linear growth rate as a function of fast ion pressure fraction $P_{hot,0}/P_{total,0}$ are shown in figure2.
- ➢ The ideal internal kink mode is unstable at zero beam ion pressure with $P_{hot,0}/P_{total,0}$ = 0. The mode structure is up-down symmetric and exhibits splitting feature due to dual q=1 surfaces, which is shown in figure 3 (a).
- ➢ When $P_{hot,0}/P_{total,0}$ >0.4, the DRF is excited, and the corresponding mode structure is shown in figure 3 (c).The mode structure is twisted with finite mode frequency.

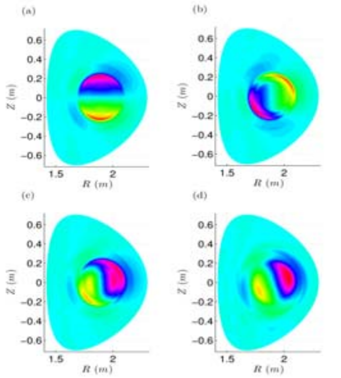

FIG. 3. Mode structures.
(a) $P_{hot,0}/P_{total,0}$ = 0, (b) $P_{hot,0}/P_{total,0}$ = 0.3,
(c) DRF with $P_{hot,0}/P_{total,0}$ = 0.6,
(d) NRF with $P_{hot,0}/P_{total,0}$ = 0.6.

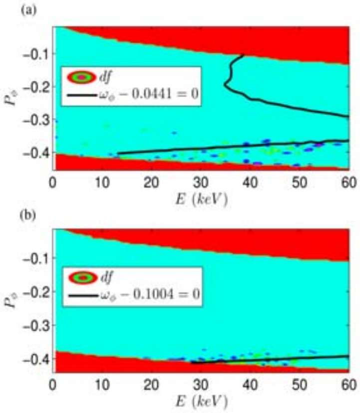

FIG. 4. Distribution function change df with Λ_0=1.0.
(a) DRF, (b) NRF.

- ➢ DRF transits to NRF with mode frequency increasing when q_{min} increases.
- ➢ Precessional resonance is satisfied for both DRF and NRF with Λ_0=1.0.

Nonlinear simulation results

DRF nonlinear evolution

- ✓ As shown in figure 5, The n=1 kinetic energy of the DRF grows continuously and cannot saturate without fluid nonlinearity.
- ✓ With both the nonlinearity of MHD and fast ions, the mode can saturate and the amplitude of the n=0 component is large.
- ✓ MHD nonlinearity is the main mechanism to cause the DRF saturation.

NRF nonlinear saturation

- ✓ The n=1 kinetic energies with and without fluid nonlinearity are compared, and the time evolutions of the n=1 components are similar.
- ✓ The saturation level of the n=1 harmonics without fluid nonlinearity is higher than that without fluid nonlinearity due to mode coupling effect.

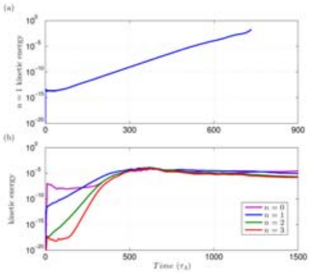

FIG. 5. DRF. (a) Without MHD nonlinearity. (b)With MHD nonlinearity.

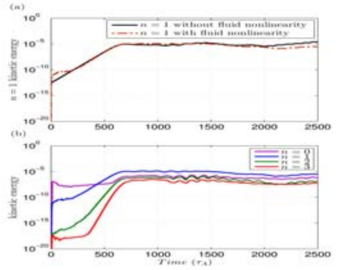

FIG. 6. NRF. (a) Time evolution of the n=1 kinetic energy. (b) Kinetic energy evolution of different toroidal modes.

CONCLUSION

- Linear simulation results show that when the beam ion pressure fraction increases to above a critical value, the DRF is driven unstable with splitting radial mode structure due to dual q=1 surfaces. The fishbone transits from the DRF to the NRF by increasing q_{min}, and the mode frequency increases with q_{min} increasing. Both the NRF and the DRF are resonant with the fast ions via the precessional resonance.

- Nonlinear results show that the DRF saturation is mainly induced by fluid nonlinearity, while the NRF saturation is mainly due to the beam ion nonlinearity.