AIP Physics of Plasmas

Linear stability and nonlinear dynamics of the fishbone mode in spherical tokamaks

Feng Wang, G. Y. Fu, J. A. Breslau, and J. Y. Liu

Citation: Physics of Plasmas (1994-present) **20**, 102506 (2013); doi: 10.1063/1.4824739
View online: http://dx.doi.org/10.1063/1.4824739
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/20/10?ver=pdfcov
Published by the AIP Publishing

PHYSICS OF PLASMAS 20, 102506 (2013)

Linear stability and nonlinear dynamics of the fishbone mode in spherical tokamaks

Feng Wang,[1] G. Y. Fu,[2,a)] J. A. Breslau,[2] and J. Y. Liu[1,b)]
[1]School of Physics and Optoelectronic Engineering, Dalian University of Technology, Dalian 116024, China
[2]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

(Received 22 August 2013; accepted 26 September 2013; published online 10 October 2013)

Extensive linear and nonlinear simulations have been carried out to investigate the energetic particle-driven fishbone instability in spherical tokamak plasmas with weakly reversed q profile and the q_{min} slightly above unity. The global kinetic-MHD hybrid code M3D-K is used. Numerical results show that a fishbone instability is excited by energetic beam ions preferentially at higher q_{min} values, consistent with the observed appearance of the fishbone before the "long-lived mode" in MAST and NSTX experiments. In contrast, at lower q_{min} values, the fishbone tends to be stable. In this case, the beam ion effects are strongly stabilizing for the non-resonant kink mode. Nonlinear simulations show that the fishbone saturates with strong downward frequency chirping as well as radial flattening of the beam ion distribution. An (m, n) = (2, 1) magnetic island is found to be driven nonlinearly by the fishbone instability, which could provide a trigger for the (2, 1) neoclassical tearing mode sometimes observed after the fishbone instability in NSTX. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4824739]

I. INTRODUCTION

In a magnetic fusion reactor such as ITER, the energetic fusion alpha particles can play a key role in plasma stability and confinement. For example, alpha particles can excite collective shear Alfvén waves which may lead to significant alpha particle loss and damage of the reactor first wall.[1] In this work we consider a particular energetic particle-driven instability, called the fishbone, in spherical tokamak plasmas. The fishbone was first discovered in the poloidal divertor experiment and was so named because the mode amplitude evolution resembles the bones of a fish.[2] The mode is driven unstable by trapped energetic beam ions via wave particle resonance between the shear Alfvén wave and the toroidal precession of trapped particles.[3] The classical fishbone has $(m, n) = (1, 1)$ kink mode structure localized within the $q = 1$ flux surface for a monotonic q profile. Here q is the magnetic field safety factor, and m/n is the poloidal and toroidal mode number for the shear Alfvén wave in a toroidal plasma. In contrast, we consider the fishbone instability associated with the non-resonant (1, 1) internal kink (NRK) mode in a spherical tokamak with weakly reversed shear q profile and the minimum q value slightly above unity. In the neutral beam-heated spherical tokamak experiments with this type of reversed shear q profile, the fishbone instability has often been observed with strong downward frequency chirping before the appearance of a steady state saturated kink mode called the "long lived mode" (LLM).[4] The instability can cause significant fast ion redistribution and losses.

In this paper, we present the first linear and nonlinear simulation results for the energetic particle-driven fishbone instability in spherical tokamak plasmas with weakly reversed shear q profiles. The global kinetic/MHD hybrid code M3D-K (Ref. 5) was used to study energetic particle interaction with the non-resonant kink mode. In the hybrid model, the thermal plasma is described by the resistive MHD model while the energetic beam ion species is treated by the drift-kinetic equation and simulated by the particle-in-cell method. The model includes the kinetic physics of the wave particle resonance between Alfvén waves and energetic particle. The model is fully nonlinear including both fluid and kinetic nonlinearity.

II. LINEAR SIMULATIONS OF ENERGETIC PARTICLE EFFECTS ON THE INTERNAL KINK MODE

This work extends our previous nonlinear MHD simulations of the NRK in NSTX, where it was shown that the non-resonant (1, 1) internal kink mode can reach a steady state saturation consistent with the long-lived mode observed in MAST.[6] Here we focus on the linear stability and nonlinear dynamics of the energetic particle-driven fishbone instability associated with the non-resonant kink mode. Our model is self-consistent including the non-perturbative effects of energetic particles on the mode in both the linear and nonlinear regimes.

We choose plasma parameters and profiles similar to a beam-heated discharge in NSTX considered previously.[7] The main parameters are major radius $R = 0.858\,m$, minor radius $a = 0.602\,m$, inverse aspect ratio $\epsilon \equiv a/R = 0.701$, toroidal magnetic field $B_0 = 0.44\,T$, number density $n_0 = 9.3 \times 10^{19}$ m^{-3}, central thermal plasma $\beta_{thermal,0} = 0.23$, and Alfvén speed $v_A \equiv B_0/(\rho_0\mu_0)^{1/2} = 7.07 \times 10^5$ m/s. The q profile versus $\sqrt{\psi}$ is shown in Fig. 1 with minimum q, q_{min}, ranging from 1.02 to 1.27, where the radial coordinate ψ is normalized poloidal flux. The beam ion distribution is a slowing-down distribution in energy[8] and a peaked distribution in pitch angle $(\Lambda \equiv \mu B_0/E)$: $f(\Lambda) \sim exp(-\frac{(\Lambda-\Lambda_0)^2}{\Delta\Lambda^2})$.

a)Electronic mail: fu@pppl.gov
b)Electronic mail: jyliu@dlut.edu.cn

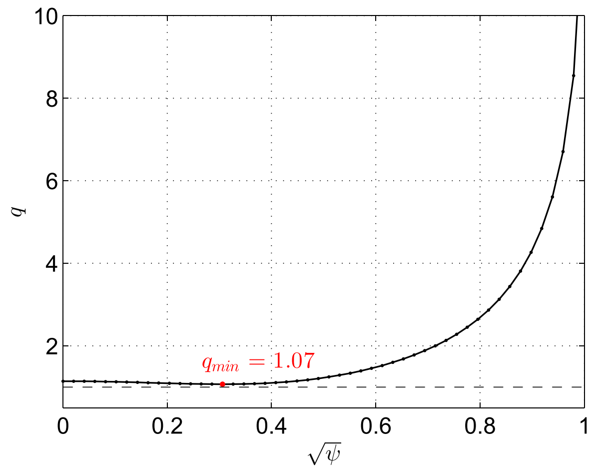

FIG. 1. Non-monotonic q profile of NSTX equilibrium with q_{min} rescaled to 1.07.

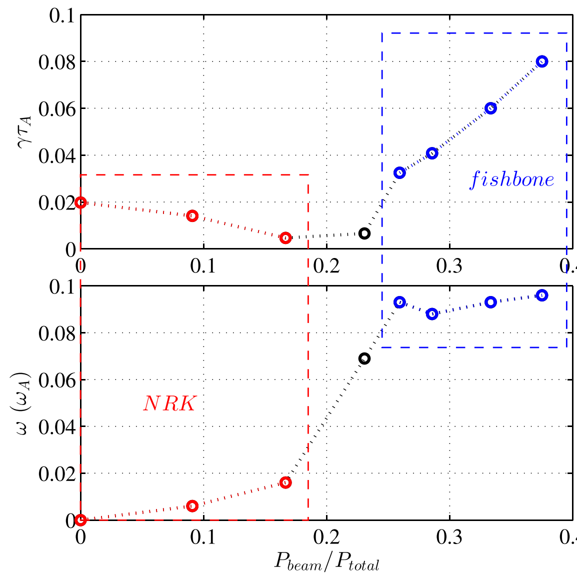

FIG. 2. Linear growth rate and mode frequency with $\beta_{thermal} = 0.30$ and $q_{min} = 1.05$ as function of P_h/P_{total}.

Figure 2 shows the linear growth rate and eigenmode frequency of the $n = 1$ mode as a function of beam ion pressure fraction at the magnetic axis P_{beam}/P_{total}. The thermal pressure is fixed for this result. The corresponding eigenmode structure is shown in Fig. 3 for two values of beam pressure fraction: $P_{beam}/P_{total} = 0$ and 0.33. At zero beam ion pressure, the mode is a pure MHD mode (non-resonant kink) with zero mode frequency and up-down symmetric structure at zero toroidal angle (Fig. 3(a)). At a small but finite beam pressure, the mode is still MHD-like with a small mode frequency. The effects of beam ions on the MHD mode are strongly stabilizing. Fig. 4 shows the dependence of the beam ion stabilization on beam ion injection energy and the peak pitch angle. We observe that the stabilizing effect is stronger for higher energy and larger pitch angle. This indicates that the stabilization is mainly due to energetic trapped particles, which agrees with the previous work for conventional tokamaks.[9–11] In contrast, at relatively large beam pressure of $P_{beam}/P_{total} > 0.2$, the mode transitions from the MHD-like mode to a fishbone-like energetic particle driven mode with a significant mode frequency. The mode structure has a twisted character (Fig. 3(b)). The frequency is comparable to the precessional drift frequency of trapped beam ions (Fig. 5), indicating that it is similar to the classical (1, 1) fishbone driven by trapped energetic particles. We have performed a scan of central pitch value, Λ_0, to study the dependence of mode character on the distribution function. Figure 6 shows the mode frequency and growth rate as a function of Λ_0. It is found that the mode is MHD-like for smaller values of Λ_0 (i.e., the distribution consists mainly of passing particles) and that the mode is fishbone-like for $\Lambda_0 \geq 0.5$ (i.e., the distribution has a significant fraction of trapped particles). This result indicates that the fishbone is driven mainly by trapped particles. Figure 7 shows the mode frequency and growth rate as a function of E_0. Since the precessional drift frequency $\omega_{pre} \propto E$, the mode frequency grows as the energetic particle energy grows while the growth rate decreases.

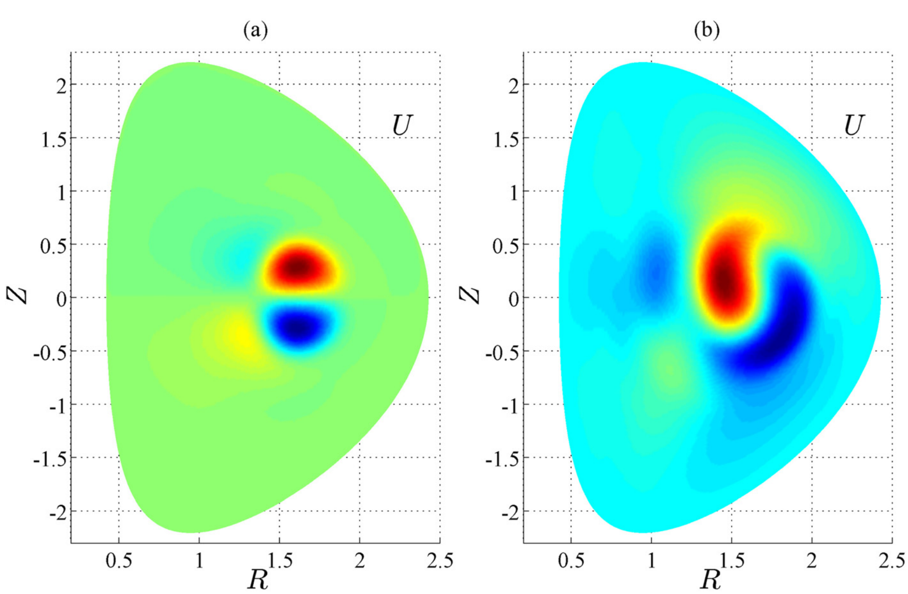

FIG. 3. The mode structure: (a) without energetic particles, (b) with energetic particles and $P_{beam}/P_{total} = 0.33$.

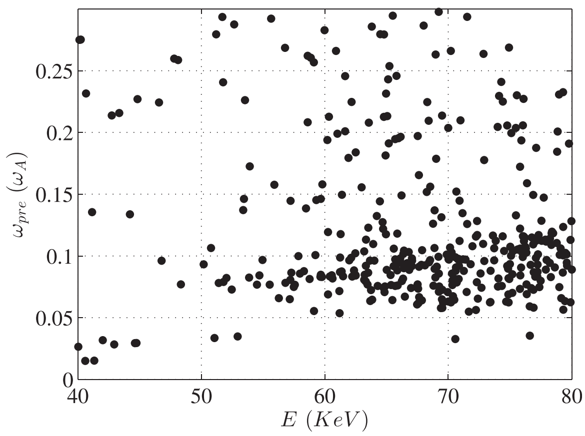

FIG. 4. Precessional drift frequency of trapped particles ($v_\perp/v_{total} = 1$) versus particle energy.

In order to better understand the stability of the fishbone, we have carried out a systematic scan in the parameter space of P_{beam}/P_{total} and q_{min}. Figure 8 shows the stability results of this scan at fixed P_{total}. The blue dots, red dots, and black circles represent the unstable fishbone, unstable MHD mode (NRK), and stable $n = 1$ mode, respectively. We observe that for lower q_{min} values, the beam ion effect is strongly stabilizing for the MHD mode, and there is no excitation of the fishbone instability. However, for higher values of q_{min}, the fishbone instability can be driven by beam ions at $P_{beam}/P_{total} > 0.1$. This result indicates that the fishbone is preferentially excited at higher q_{min} values, consistent with the experimental observation of the appearance of the fishbone before the LLM as q_{min} drops in time.[4] Physically this q_{min} dependence of fishbone instability is due to weaker continuum damping at higher q_{min}.

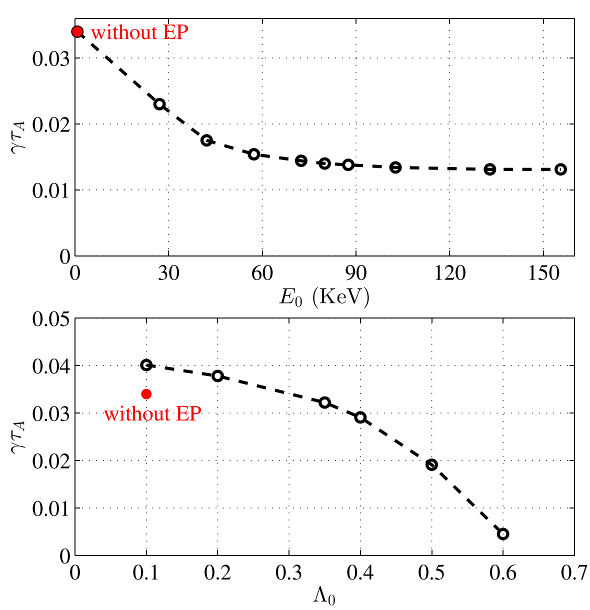

FIG. 5. Energetic particle effect on the NRK ($\omega \simeq 0$) linear stability: linear growth rate versus energetic particle energy with $P_{beam}/P_{total} = 0.09$, $q_{min} = 1.05$ (top), and linear growth rate versus energetic particle pitch angle with $P_{beam}/P_{total} = 0.17$, $q_{min} = 1.05$ (bottom).

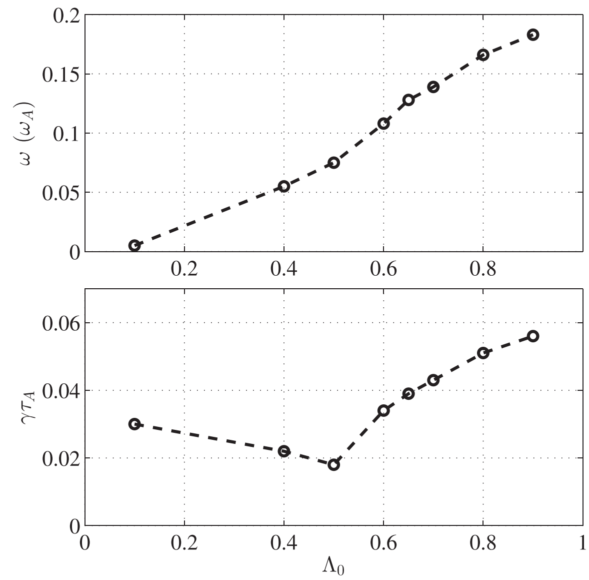

FIG. 6. Mode frequency and linear growth rate versus energetic particle pitch angle with $P_{beam}/P_{total} = 0.35$, $q_{min} = 1.12$.

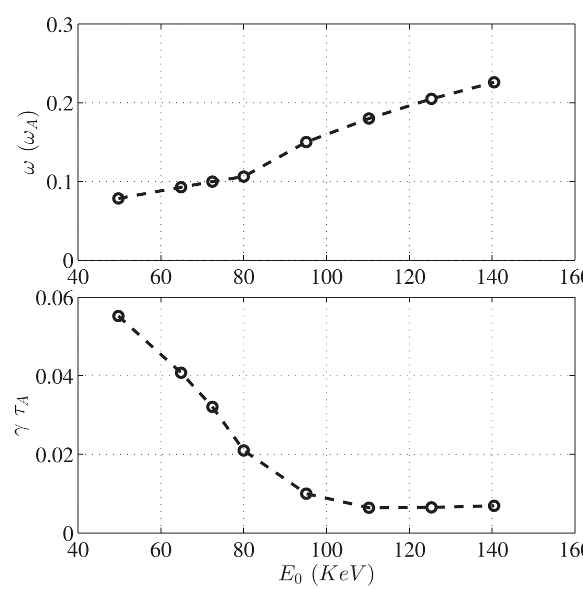

FIG. 7. Fishbone mode growth rate and frequency versus energetic particle energy with $P_{beam}/P_{total} = 0.35$, $q_{min} = 1.05$.

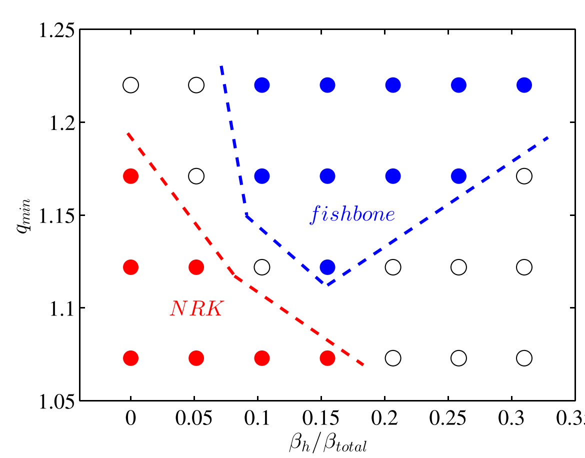

FIG. 8. The NRK and the fishbone stability diagram with inclusion of stability boundary in q_{min} and β_h/β_{total} space (fixed total pressure).

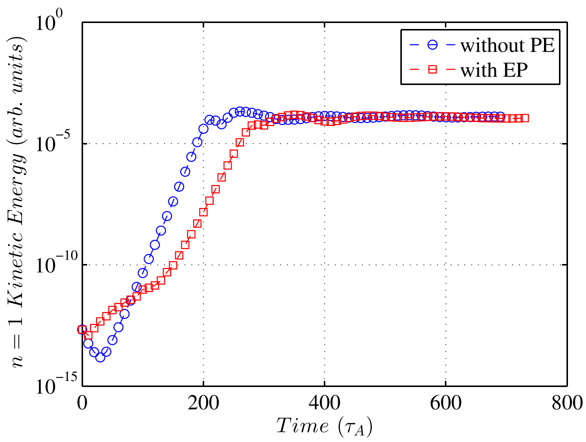

FIG. 9. The NRK mode kinetic energy evolution of $n = 1$ component.

III. NONLINEAR SIMULATIONS OF ENERGETIC PARTICLE INTERACTION WITH THE INTERNAL KINK MODE

This section will describe the nonlinear interaction between energetic particles and an $n = 1$ internal kink mode (including the NRK mode and the fishbone branches). Figure 9 compares the $n = 1$ component of the kinetic energy of the NRK mode with and without energetic particle, which shows a stabilizing effect on the linear phase, while it has weak effects on the nonlinear saturation level. Figure 10 represents the energetic particle redistribution induced by the NRK nonlinear evolution, which agrees with experimental results in NSTX.[12] The results also indicate that the redistribution mainly occurs inside the q_{min} surface, and when the mode saturates ($time \simeq 300\tau_A$), the distribution function reaches a steady state.

We now proceed to present our nonlinear simulation results of the $n = 1$ fishbone. Figure 11(a) shows the nonlinear evolution of the $n = 0$, 1, 2, and 3 components of the mode energy. The corresponding mode frequency evolution is shown in Fig. 11(b). We observe that the fishbone starts to saturate at about $time = 250\ \tau_A$ when the frequency chirps down strongly. The $n = 1$ mode is saturated around an approximate steady state. The $n = 2$ and $n = 3$ mode amplitudes are much lower, indicating that the $n = 1$ mode is still the dominant mode in the nonlinear saturation phase. These nonlinear results are similar to those of the classical (1, 1) fishbone.[8] The nonlinear saturation is due to radial flattening of the beam ion distribution, which is observed in our simulations at mode saturation (Fig. 12). Compared to the redistribution induced by the NRK mode, the flattening is also mainly inside the q_{min} surface, but with wave particle resonance, the redistribution effect of the fishbone is stronger, and even after the mode has saturated, it still induces energetic particle transport. In addition to these nonlinear results, we find that a (2, 1) magnetic island is induced nonlinearly

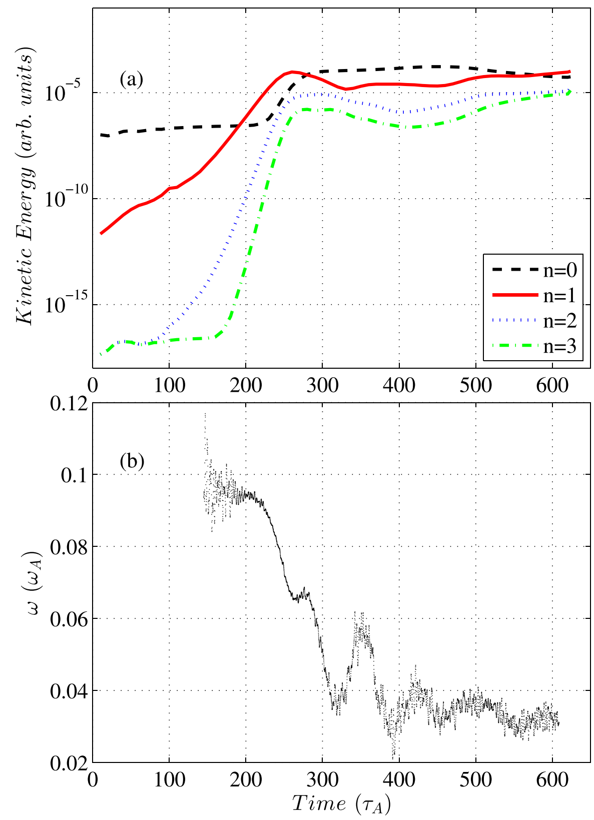

FIG. 11. Nonlinear evolution of fishbone mode with $P_{beam}/P_{total} = 0.35$, $q_{min} = 1.05$: (a) the kinetic energy by toroidal mode number, (b) mode frequency.

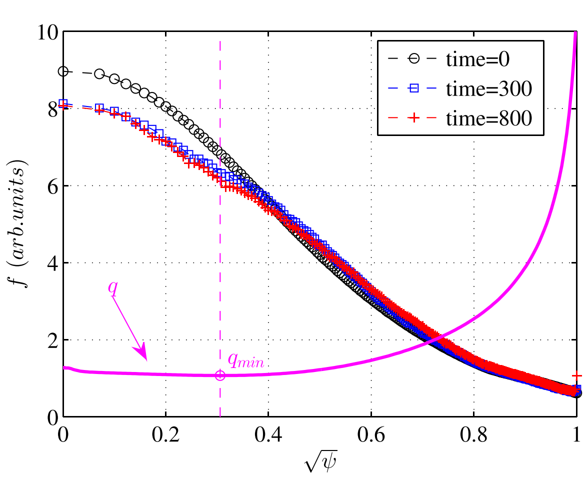

FIG. 10. The NRK induces energetic particle redistribution.

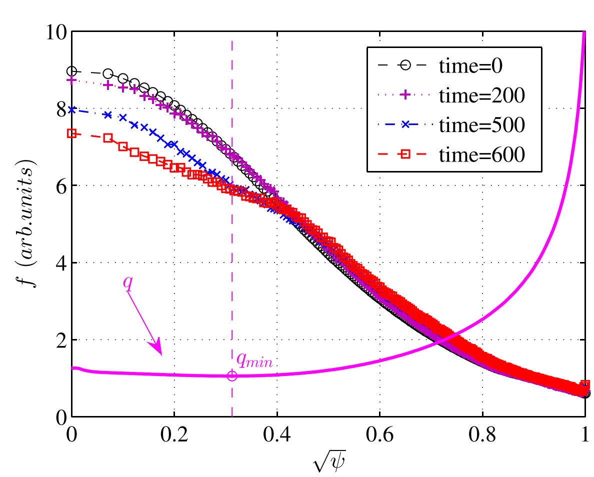

FIG. 12. The fishbone mode induces energetic particle redistribution at different time frames.

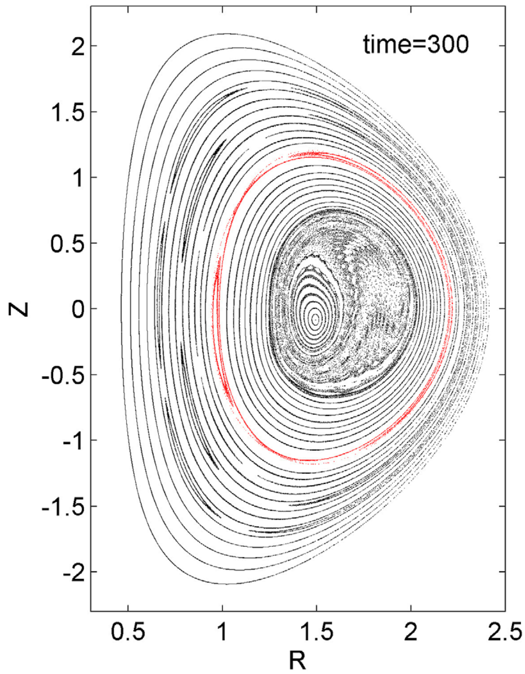

FIG. 13. Poincaré plot of magnetic surfaces at $time = 300\,\tau_A$.

by the fishbone around the $q = 2$ flux surface, as shown in Fig. 13. Additional magnetic islands are also induced beyond the $q = 2$ surface. These fishbone-induced seed magnetic islands could trigger neoclassical tearing modes as sometimes they observed after the fishbone instability in NSTX[13] and also in conventional tokamaks.[14]

IV. SUMMARY

In conclusion, we have performed extensive linear and nonlinear hybrid simulations to investigate energetic particle effect on the NRK and the energetic particle-driven fishbone instability in spherical tokamak plasmas. Numerical results from the M3D-K code show that the trapped energetic particles have strong stabilizing effect on the NRK mode, and the fishbone instability is excited by trapped beam ions preferentially at higher q_{min} values, consistent with the observed appearance of the fishbone before the "long-lived mode" in NSTX and MAST experiments. Nonlinear simulations show that the fishbone saturates with strong downward frequency chirping as well as radial flattening of the beam ion distribution inside the q_{min} surface. A (2, 1) magnetic island is induced nonlinearly by the fishbone instability, which could provide a trigger for the (2, 1) neoclassical tearing mode sometimes observed after the fishbone instability in NSTX.[13] Nonlinear results of energetic particle interaction with the NRK mode show that without wave-particle resonance, the NRK mode can also induce significant energetic particle redistribution, which agrees with experimental results. These results have important implications for the stability of global MHD modes and the fishbone instability as well as energetic particle transport in present tokamak plasmas and future burning plasmas such as ITER. In particular, the fishbone instability could be driven unstable in the advanced tokamak operating regime with weakly reversed shear q profile and q_{min} near integer values.

ACKNOWLEDGMENTS

G. Y. Fu acknowledges useful discussion with Dr. Eric Fredrickson regarding the fishbone instability observed in NSTX plasmas. He also thanks Dr. Jay Johnson and Dr. Peter Damiano for discussion on similar energetic particle-driven instabilities in magnetoshere. This work was supported by U.S. Department of Energy under DE-AC02-09CH11466, National Magnetic Confinement Fusion Science Program of China under Contract Nos. 2013GB107003 and 2013GB111001, and National Natural Science Foundation of China under Contract No. 11375039. The simulations were carried out using the Hopper computer at NERSC and the HPCC3 computer at Zhejiang University.

[1] H. Duong, W. Heidbrink, E. Strait, T. Petrie, R. Lee, R. Moyer, and J. Watkins, "Loss of energetic beam ions during TAE instabilities," Nucl. Fusion **33**, 749–765 (1993).
[2] K. McGuire, R. Goldston, M. Bell, M. Bitter, K. Bol, K. Brau, D. Buchenauer, T. Crowley, S. Davis, F. Dylla, H. Eubank, H. Fishman, R. Fonck, B. Grek, R. Grimm, R. Hawryluk, H. Hsuan, R. Hulse, R. Izzo, R. Kaita, S. Kaye, H. Kugel, D. Johnson, J. Manickam, D. Manos, D. Mansfield, E. Mazzucato, R. McCann, D. McCune, D. Monticello, R. Motley, D. Mueller, K. Oasa, M. Okabayashi, K. Owens, W. Park, M. Reusch, N. Sauthoff, G. Schmidt, S. Sesnic, J. Strachan, C. Surko, R. Slusher, H. Takahashi, F. Tenney, P. Thomas, H. Towner, J. Valley, and R. White, "Study of high-beta magnetohydrodynamic modes and fast-ion losses in PDX," Phys. Rev. Lett. **50**, 891–895 (1983).
[3] L. Chen, R. B. White, and M. N. Rosenbluth, "Excitation of internal kink modes by trapped energetic beam ions," Phys. Rev. Lett. **52**, 1122–1125 (1984).
[4] I. Chapman, M.-D. Hua, S. Pinches, R. Akers, A. Field, J. Graves, R. Hastie, and C. Michael, "Saturated ideal modes in advanced tokamak regimes in MAST," Nucl. Fusion **50**, 045007 (2010).
[5] W. Park, E. V. Belova, G. Y. Fu, X. Z. Tang, H. R. Strauss, and L. E. Sugiyama, "Plasma simulation studies using multilevel physics models," Phys. Plasmas **6**, 1796 (1999).
[6] F. Wang, G. Y. Fu, J. A. Breslau, K. Tritz, and J. Y. Liu, "Simulation of non-resonant internal kink mode with toroidal rotation in the national spherical torus experiment," Phys. Plasmas **20**, 072506 (2013).
[7] J. Breslau, M. Chance, J. Chen, G. Fu, S. Gerhardt, N. Gorelenkov, S. Jardin, and J. Manickam, "Onset and saturation of a non-resonant internal mode in NSTX and implications for AT modes in ITER," Nucl. Fusion **51**, 063027 (2011).
[8] G. Y. Fu, W. Park, H. R. Strauss, J. Breslau, J. Chen, S. Jardin, and L. E. Sugiyama, "Global hybrid simulations of energetic particle effects on the n = 1 mode in tokamaks: Internal kink and fishbone instability," Phys. Plasmas **13**, 052517 (2006).
[9] F. Porcelli, "Fast particle stabilisation," Plasma Phys. Controlled Fusion **33**, 1601–1620 (1991).
[10] R. J. Hastie, T. C. Hender, B. A. Carreras, L. A. Charlton, and J. A. Holmes, "Stability of ideal and resistive internal kink modes in toroidal geometry," Phys. Fluids **30**, 1756 (1987).
[11] B. Coppi, R. Hastie, S. Migliuolo, F. Pegoraro, and F. Porcelli, "Suppression of internal plasma oscillations by trapped high energy nuclei," Phys. Lett. A **132**, 267–272 (1988).
[12] J. Menard, R. Bell, D. Gates, S. Kaye, B. LeBlanc, F. Levinton, S. Medley, S. Sabbagh, D. Stutman, K. Tritz, and H. Yuh, "Observation of instability-induced current redistribution in a spherical-torus plasma," Phys. Rev. Lett. **97**, 095002 (2006).
[13] S. Gerhardt, D. Brennan, R. Buttery, R. La Haye, S. Sabbagh, E. Strait, M. Bell, R. Bell, E. Fredrickson, D. Gates, B. LeBlanc, J. Menard, D. Stutman, K. Tritz, and H. Yuh, "Relationship between onset thresholds, trigger types, and rotation shear for the m/n = 2/1 neoclassical tearing mode in a high-β spherical torus," Nucl. Fusion **49**, 032003 (2009).
[14] A. Gude, S. Günter, S. Sesnic, and A. U. Team, "Seed island of neoclassical tearing modes at ASDEX upgrade," Nucl. Fusion **39**, 127–131 (1999).