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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*

Outline

- Introduction
- M3D-K model and basic parameters
- Linear simulation results
- Nonlinear simulation results
- Summary

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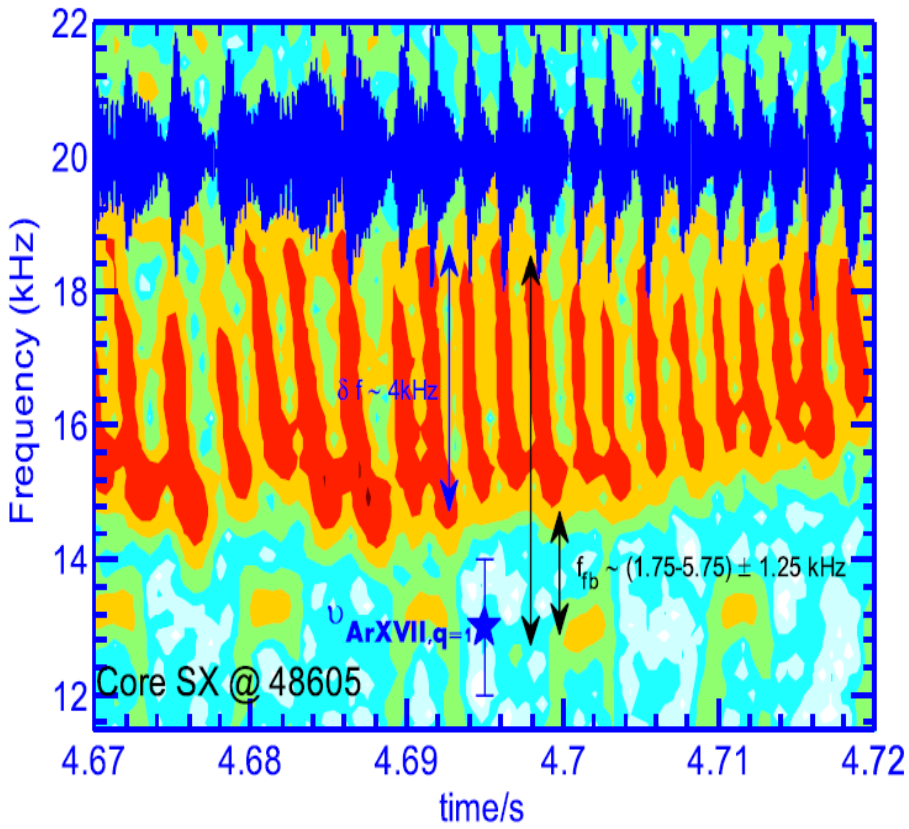
Introduction I

- 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.

- Fishbone was first discovered in PDX with NBI[K. McGuire et al. PRL 1983], which is typically an internal mode with toroidal mode number n = 1 and dominant poloidal mode number m = 1.



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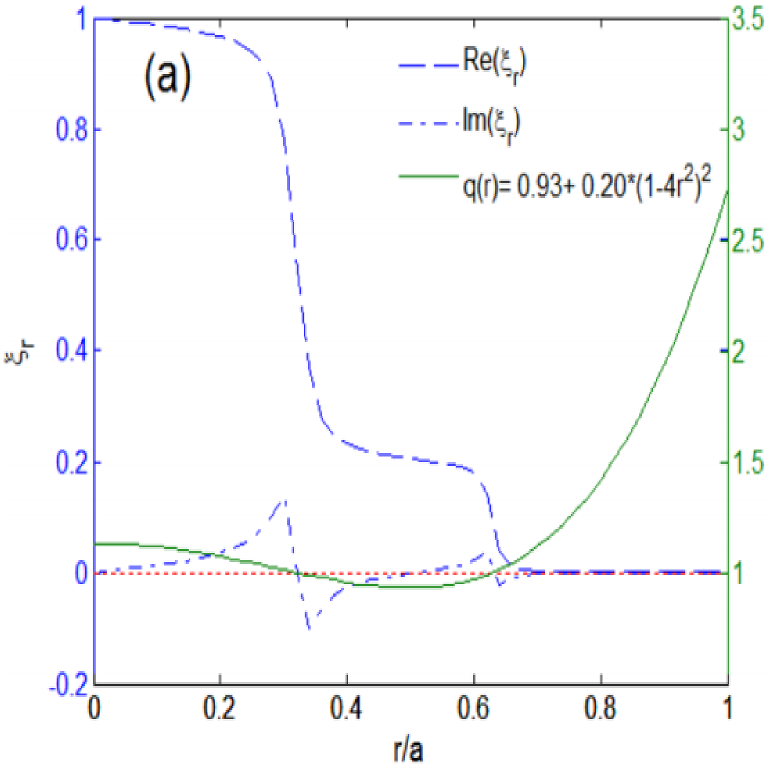
Introduction II

- A non-monotonic safety factor profile with a reversed magnetic shear configuration has been proposed as an advanced scenario for future ITER operation. For the consideration of the fishbone instability, there are two different conditions: the minimum value of safety factor q_{min} is less or a little larger than unity.
- 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.



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Basic parameters and initial profiles

Main parameters:

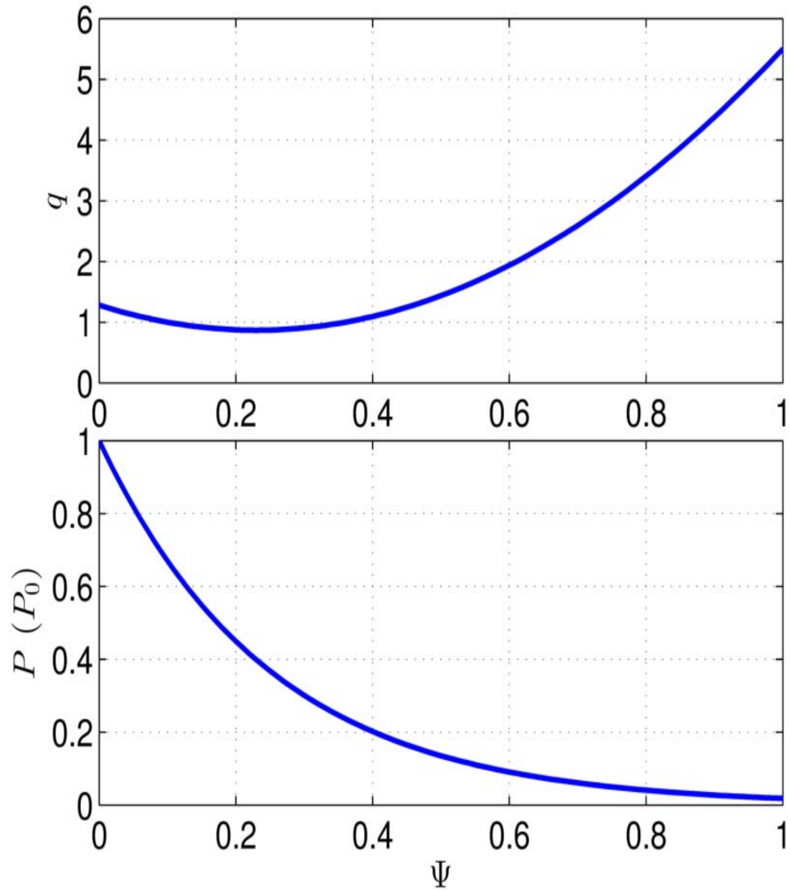
major radius: R_0=1.86 m
minor radius: a=0.44 m
elongation: κ=1.60
triangularity: δ=0.43
toroidal magnetic field: B_0=1.75 T
central density: $n_0=5.28\times10^{19}$ m^{-3}
central total plasma beta: $\beta_{total,0}$=3.52%
central beam ion beta: $\beta_{hot,0}$=0.86%

Beam ion distribution function:

$$f = c\left(\sum_{i=1}^{3} c_i \frac{H(v_0/\sqrt{i} - v)}{v^3 + v_c^3}\right) exp(-(\Lambda - \Lambda_0)^2/\Delta\Lambda^2) exp(-\langle\Psi\rangle/\Delta\Psi),$$

The injection energy of NBI is E_0 = 60 keV

$$\Lambda \equiv \mu B_0/E \qquad \Lambda_0 = 1.0,\ \Delta\Lambda = 0.2,\ \ \Delta\Psi = 0.25$$



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Models used in M3D/M3D-K

Resistive MHD model+EP pressure coupling

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla P - \nabla\cdot\mathbf{P}_h + \mathbf{J}\times\mathbf{B}$$

$$\mathbf{J} = \nabla\times\mathbf{B}, \quad \frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

$$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{J}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

$$\frac{dp}{dt} = -\gamma p\nabla\cdot\mathbf{v} + \rho\nabla\cdot\overleftrightarrow{\kappa}\cdot\nabla\frac{p}{\rho}$$

CGL form

$$\mathrm{P}_h = P_\perp\mathrm{I} + (P_\parallel - P_\perp)\mathrm{bb}$$

Guiding center distribution

$$F = F(\mathrm{X}, v_\parallel, \mu) = \sum_i \delta(\mathrm{X} - \mathrm{X}_i)\delta(v_\parallel - v_{\parallel,i})\delta(\mu - \mu_i)$$

Gyrokinetic or drift kinetic equations

$$\frac{d\mathrm{X}}{dt} = \frac{1}{B^{\star\star}}[v_\parallel\mathrm{B}^\star - \mathrm{b}_0\times(\langle\mathrm{E}\rangle - \frac{1}{e}\mu\nabla(B_0 + \langle\delta B\rangle))]$$

$$m\frac{dv_\parallel}{dt} = \frac{e}{B^{\star\star}}\mathrm{B}^\star\cdot[\langle\mathrm{E}\rangle - \frac{1}{e}\mu\nabla(B_0 + \langle\delta B\rangle)]$$

$$\mathbf{B}^\star = \mathbf{B}_0 + \langle\delta\mathbf{B}\rangle + \frac{mv_\parallel}{q}\nabla\times\mathbf{b}_0, \quad B^{\star\star} = \mathbf{B}^\star\cdot\mathbf{b}_0$$

G. Y. Fu et al., Phys. Plasmas 2006

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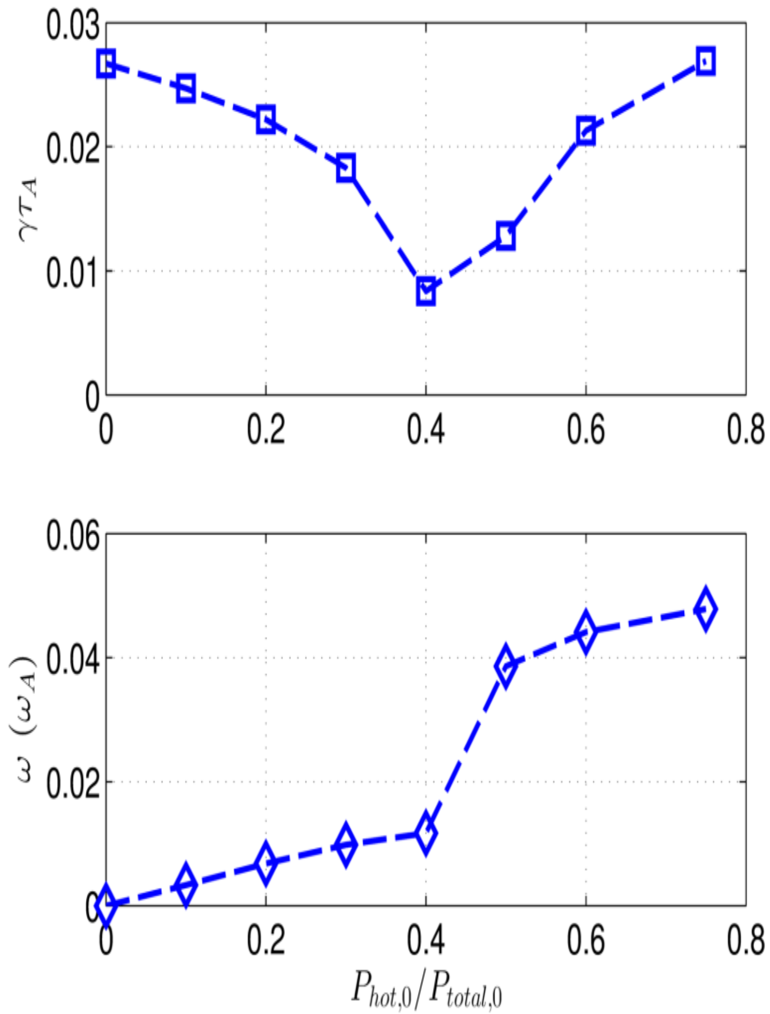
Fishbone is excited when beam pressure increases



- $P_{hot,0}/P_{total,0}$ =0. the ideal internal kink is unstable.
- $P_{hot,0}/P_{total,0}$ increases from 0 to 0.4, the mode is firstly stabilized.
- $P_{hot,0}/P_{total,0}$ is larger than 0.4, the fishbone instability (dual resonant fishbone) is excited.

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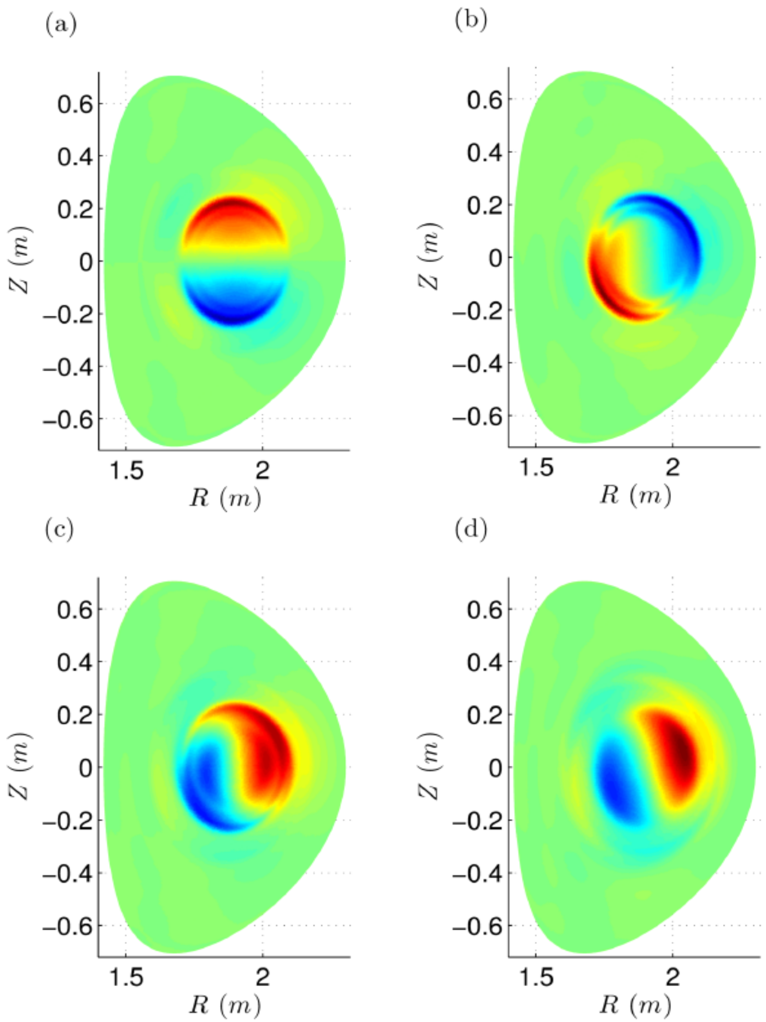
Mode structure changes when beam pressure increases



- $P_{hot,0}/P_{total,0}$=0: up-down symmetric mode structure with splitting feature due to double q=1 surfaces (Fig. (a)).
- $P_{hot,0}/P_{total,0}$=0.3: the mode structure shows a twisted feature with finite mode frequency (Fig. (b)).
- $P_{hot,0}/P_{total,0}$=0.6: more twisted dual resonant fishbone (DRF) mode structure (Fig. (c)).
- $P_{hot,0}/P_{total,0}$=0.5: non-resonant fishbone (NRF) with q_0>1(Fig. (d)).

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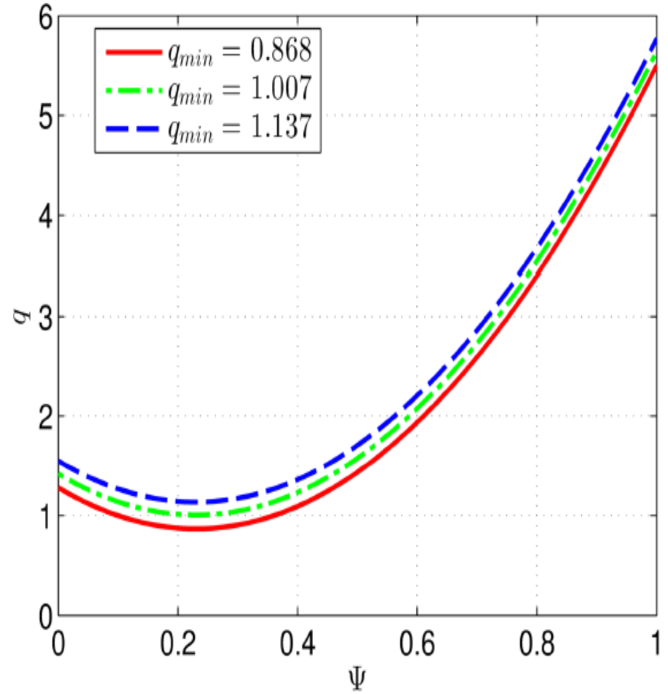
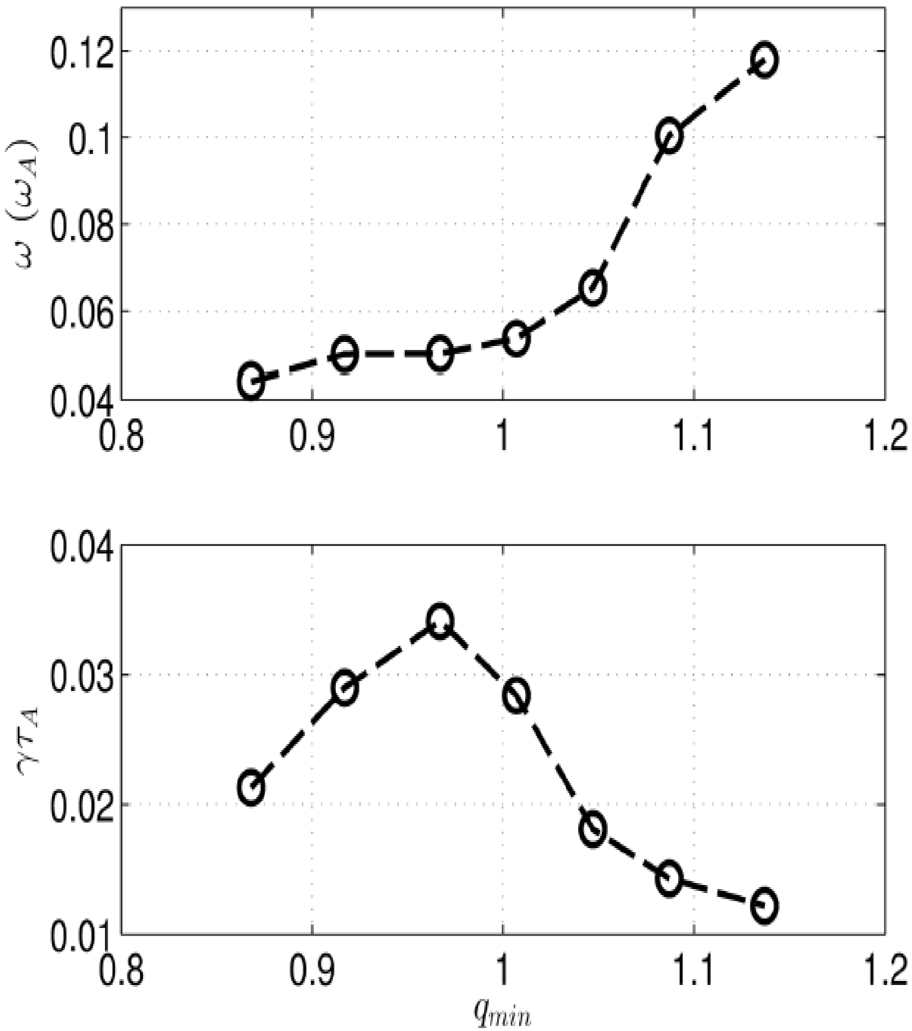
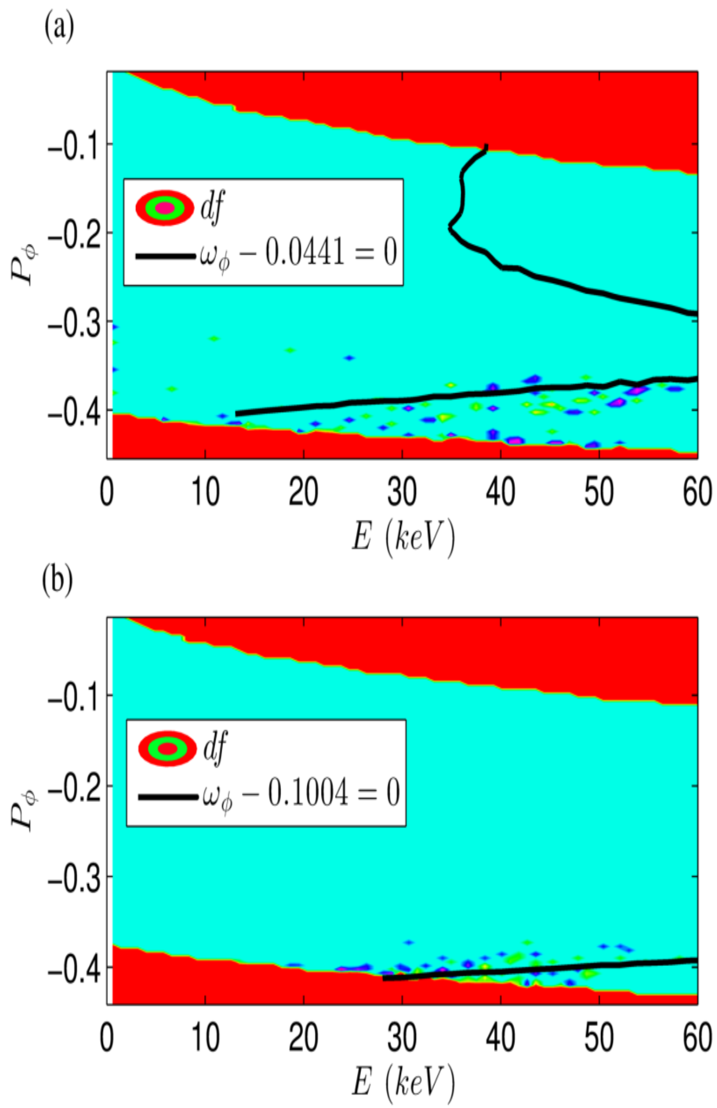
Mode changes when q_{min} changes





- **DRF transits to NRF with higher mode frequency.**

Large df structure is consistent with resonant condition



- **Resonant condition:**

$$n\omega_\phi + p\omega_\theta - \omega = 0,$$

- **For both the DRF and NRF, the resonant condition $\omega = \omega_\phi$ is satisfied.**

- **The energetic particles which are resonant with the NRF are located more centrally in radial direction, and ω_ϕ increases when the radial location of the trapped energetic particles decreases. As a result, the frequency of the NRF is higher than the DRF.**

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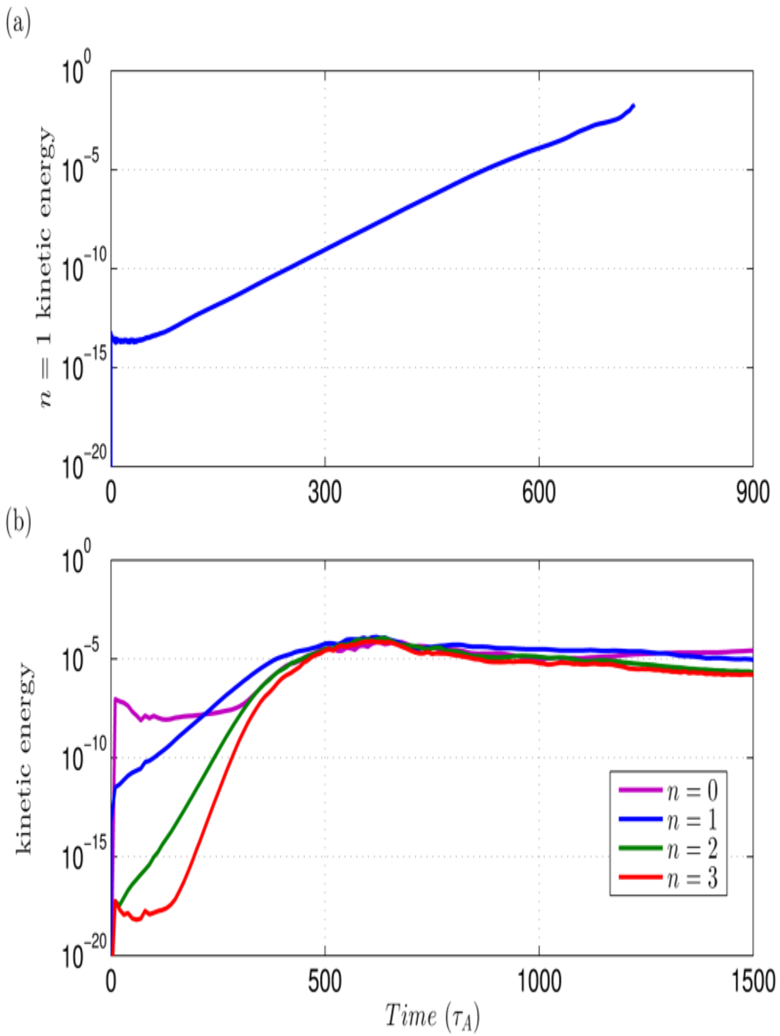
Nonlinear saturation of DRF is due to MHD nonlinearity



- **Figure (a) shows that the kinetic energy of the n = 1 fishbone instability grows to a very large amplitude and does not saturate without MHD nonlinearity.**
- **However, with the nonlinearity of both energetic particles and MHD, the mode saturates with a large n = 0 component, as shown in figure (b). As a result, the DRF saturation is due to MHD nonlinearity.**

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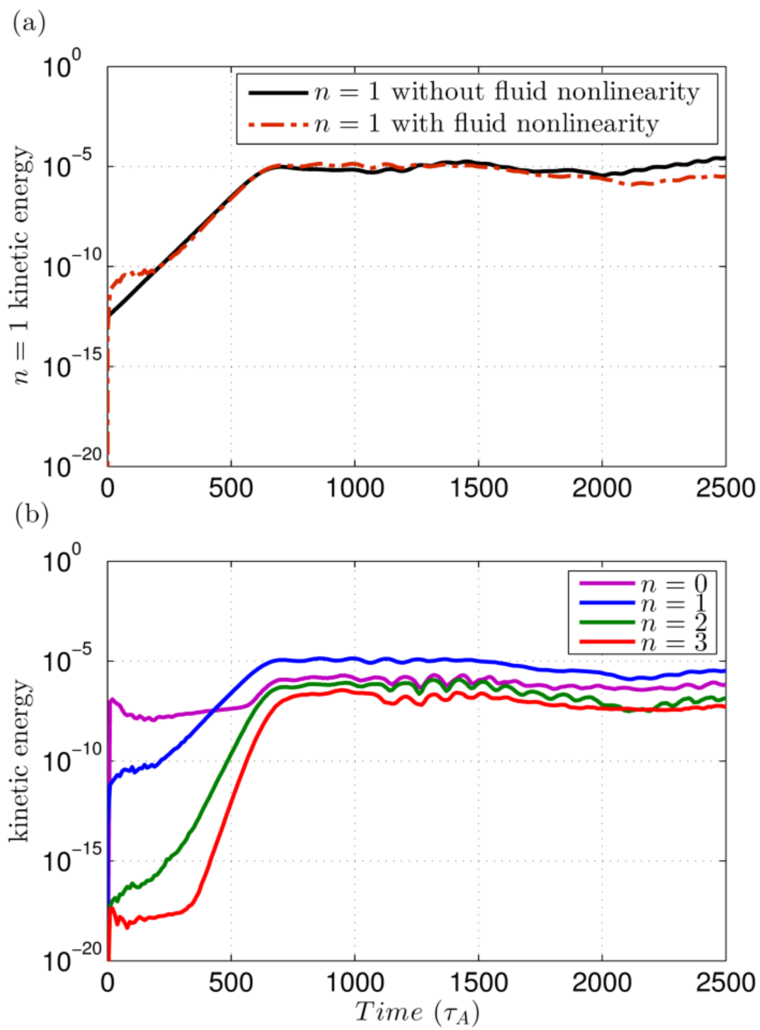
Nonlinear saturation of NRF is due to EP nonlinearity



- **Time evolutions of the n=1 component of the kinetic energy without and with MHD nonlinearity are similar. However, due to the mode coupling effect, the saturation level with MHD nonlinearity is lower than that without MHD nonlinearity.**
- **Time evolution of toroidal modes up to the n = 3 mode with MHD nonlinearity is simulated. We find that different modes are coupled together with the n = 1 component being dominant.**

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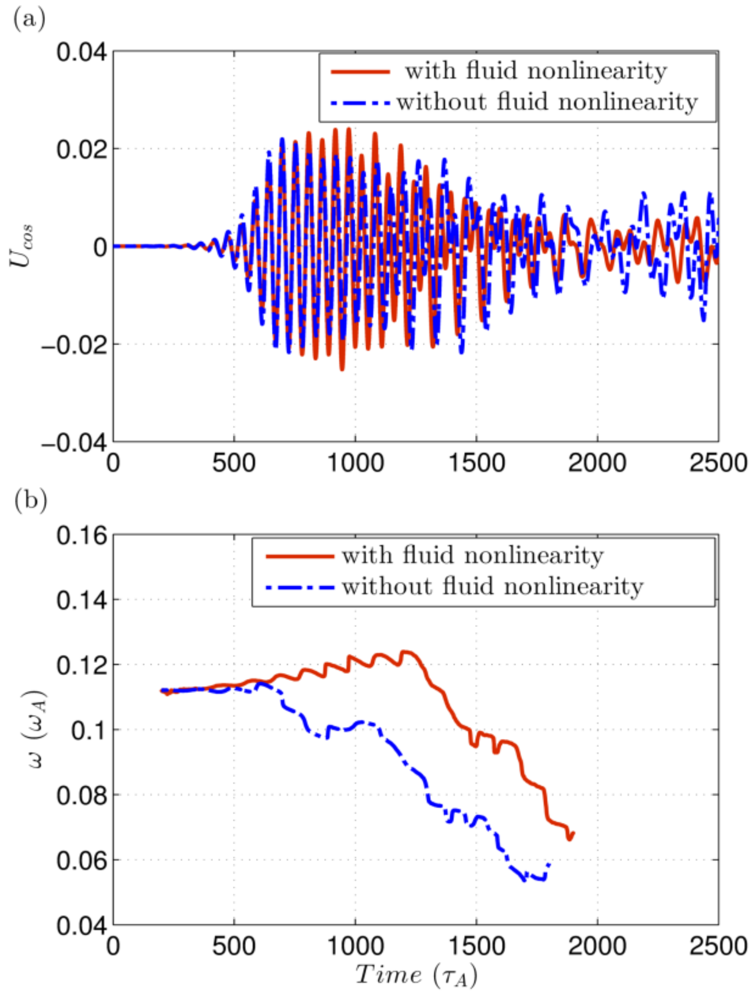
The NRF frequency chirps down during nonlinear phase



- **The NRF amplitude firstly starts to grow and then saturates. Moreover, the NRF amplitude without fluid nonlinearity decays slower than that with fluid nonlinearity.**
- **The NRF frequencies both chirp down nonlinearly with or without MHD nonlinearity. However, for the NRF with fluid nonlinearity, the mode frequency firstly increases and then chirps down.**

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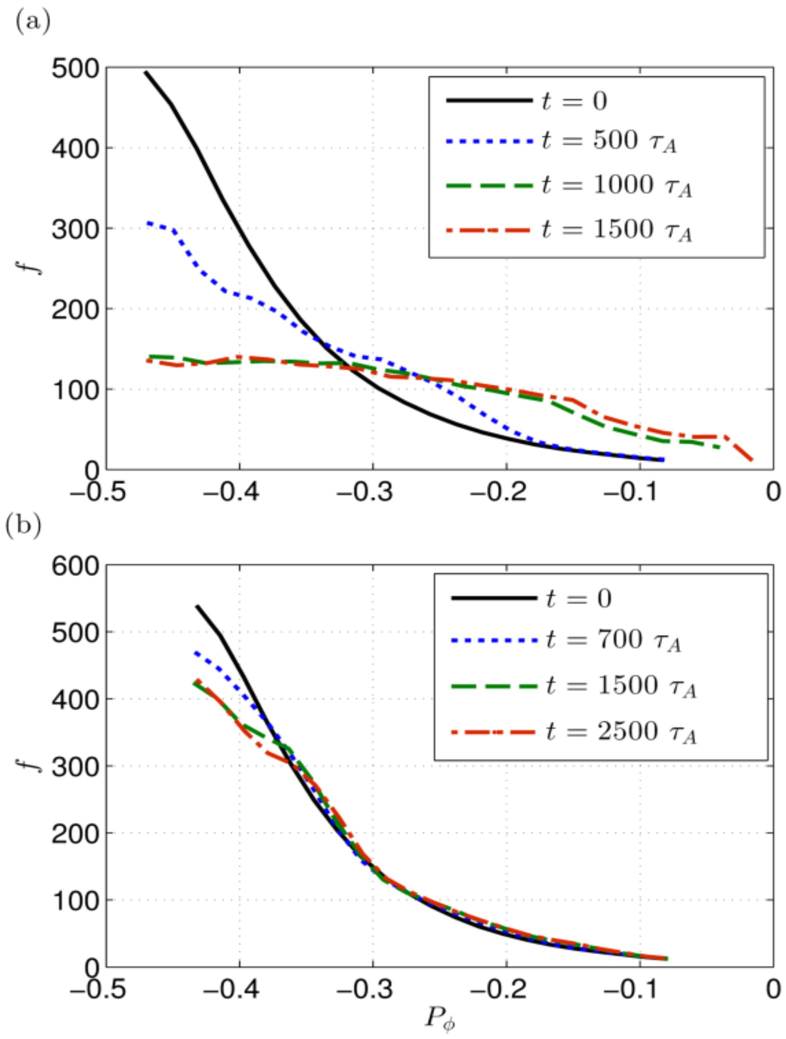
Fast ions are redistributed due to DRF or NRF



- **After the saturation of the DRF (at t = 500 τ_A), fast ions are strongly redistributed. Then, during the nonlinear saturation of the DRF, the distribution of the beam ions becomes flatter in the core region.**
- **In comparison with the redistribution induced by the DRF, and the redistribution level of the fast ions due to the NRF is weaker.**

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Summary and conclusions

A systematic study of the linear stability and nonlinear dynamics of the fishbone instabilities with reversed safety factor profile has been performed by the global kinetic-MHD code M3D-K. Equilibrium profiles and parameters are chosen based on EAST-like conditions.

- **Linear simulations show that the DRF is excited by the trapped beam ions when the fast ion pressure increases to exceed a critical value, and the mode structure of DRF exhibits splitting feature due to double q = 1 surfaces. When q_{min} increases from below unity to above unity, the fishbone instability transits from the DRF to the NRF, and the mode frequency of the NRF is higher than the DRF as the NRF is resonant with fast ions with larger precessional frequency.**
- **Nonlinear simulations show that the saturation of the DRF is due to MHD nonlinearity with a large n = 0 component. However, the saturation of the NRF is mainly due to the nonlinearity of fast ions, and the frequency of the NRF chirps down nonlinearly.**

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