Nonlinear Dynamics of Energetic Particle-driven Fishbone Instability in Tokamak Plasmas

Guoyong Fu

Princeton Plasma Physics Laboratory

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J. Breslau, J. Chen, S. Jardin, H. Strauss, L. Sugiyama,
W. Park, N. Gorelenkov, S. Klasky

Brief Review of Fishbone I

- **Fishbone instability was first discovered on the PDX tokamak. The instability was named for its signature magnetic signal**

  (K. McGuire et al, Phys. Rev. Lett., 1983).

- **The instability was later observed in others tokamaks and stellarators.**

- **The instability has signature bursting behavior with strong chirping in mode frequency.**

Fishbone in PDX (McGuire et al, 1983)

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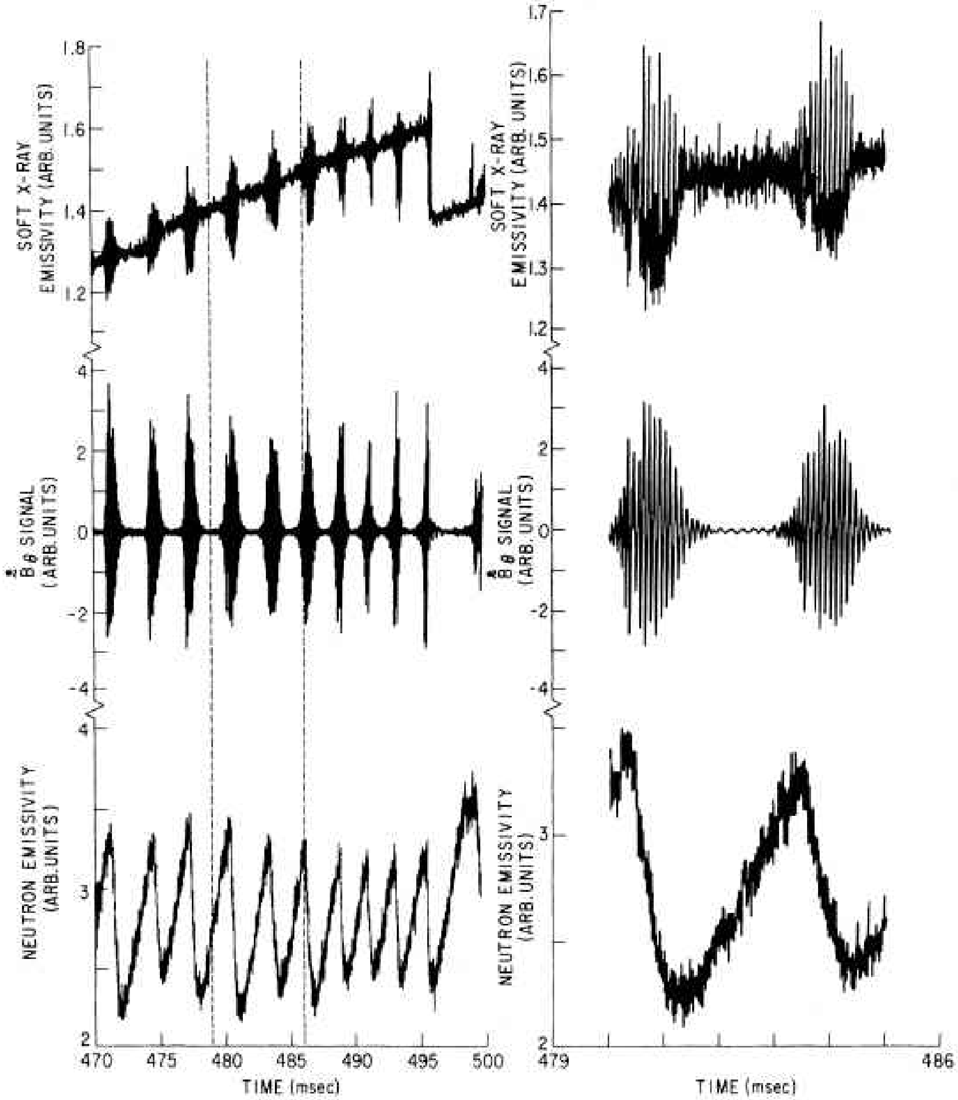
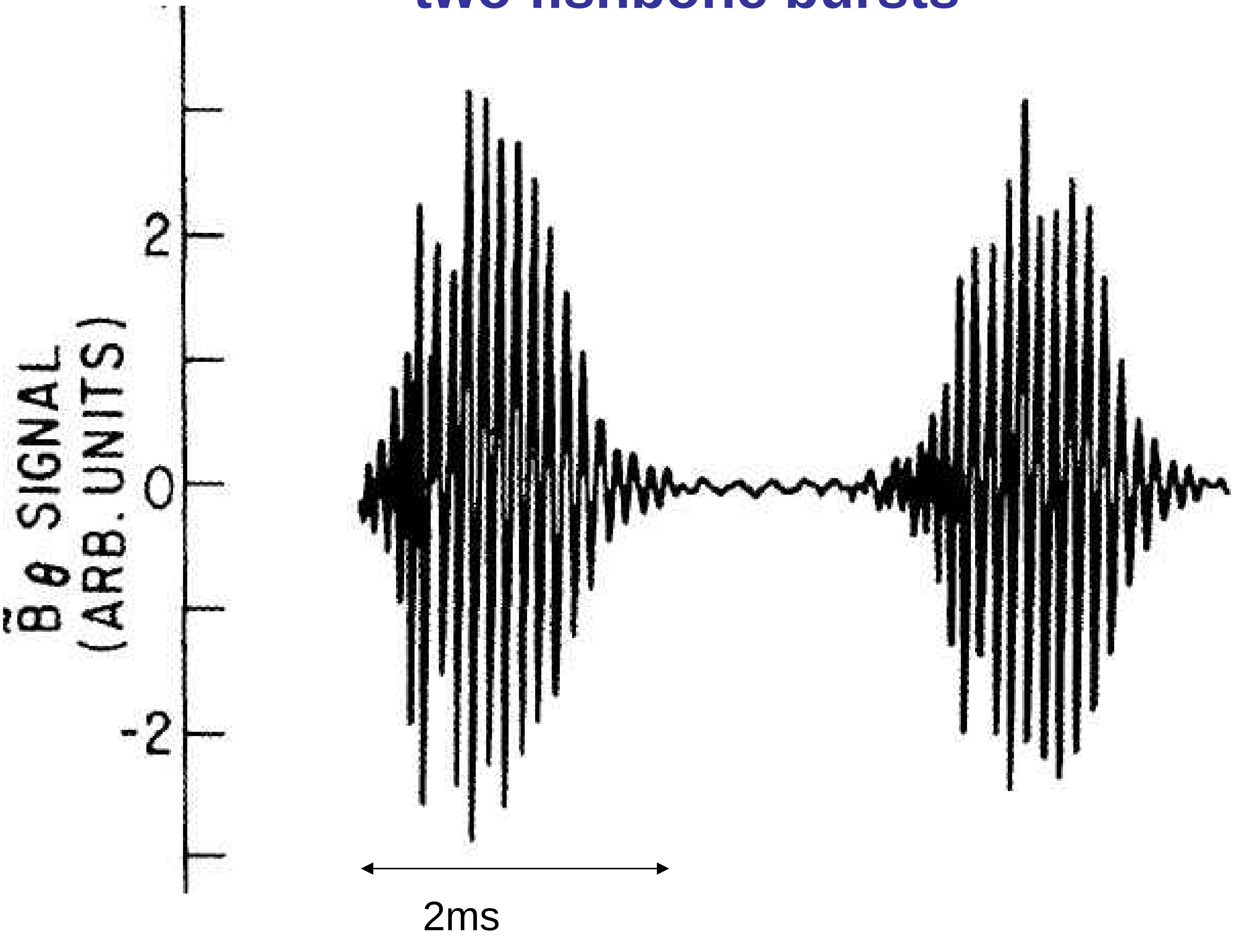


FIG. 1. The time evolution of the soft-x-ray emission along a central chord, the $\dot{B}_\theta$ signal from a coil near the outer wall of the vacuum vessel, and the fast neutron flux. Expansion of the data near two "fishbones" is also shown.

two fishbone bursts



Brief Review of Fishbone: Linear Theory

- **The instability was explained as a n/m=1/1 internal kink mode resonantly destabilized by trapped beam ions:**

precessional branch: $\omega \sim \omega_{dh}$ (L. Chen et al , P.R.L., 1984)

ω_* branch: $\omega \sim \omega_{*i}$ (B. Coppi et al, P.R.L., 1985)

Brief Review of Fishbone: Nonlinear Theory

- **Semi-empirical model** (Predator-Prey model)

  nonlinear saturation and bursting behavior was explained by particle loss induced by the fishbone mode.

  (e.g., Heidbrink, 1993)

- **Nonlinear Kinetic model**

  The strong frequency chirping can be explained by hole-clump theory of Berk and Breizman.

  Candy et al. did a hybrid simulation of a complete fishbone oscillation by using a simplified self-consistent kinetic model. A strong frequency chirping was shown to be caused by particle nonlinearity. However, MHD nonlinearity was not included.

  (J. Candy et al., Phys. Plasmas, 1999)

- **Nonlinear MHD model**

  Odblom et al. investigated MHD nonlinearity by assuming a linear energetic particle response. Near marginal stability, the mode has double layer structure near q=1 surface and MHD nonlinearity is strongly destabilizing.

  (A. Odblom et al., Phys. Plasmas, 2002)

This Work

- We will investigate nonlinear dynamics of fishbone instability by using a comprehensive hybrid model: full MHD plus energetic particles.

- Mode structure is self-consistently determined.

- Both particle nonlinearity and fluid nonlinearity are included.

Outline

- Introduction
- M3D Hybrid Model
- M3D code
- Linear Simulations of Fishbone
- Nonlinear Simulations of Fishbone
- Conclusions

M3D XMHD Model

$$\rho \frac{d\mathbf{v}}{dt} + \rho(\mathbf{v}_\mathbf{i}^{*} \cdot \nabla)\mathbf{v}_\perp = -\nabla P - \nabla \cdot \mathbf{P}_h + \mathbf{J} \times \mathbf{B} - \mathbf{bb} \cdot \nabla \cdot \Pi_i$$

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

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} - \nabla_{||} P_e / en - \mathbf{bb} \cdot \nabla \cdot \Pi_e$$

$$\partial P / \partial t + \mathbf{v} \cdot P = -\gamma P \nabla \cdot \mathbf{v} + \ldots..$$

$$\partial P_e / \partial t + \mathbf{v} \cdot P_e = -\gamma P_e \nabla \cdot \mathbf{v} + \ldots..$$

- Pressure tensor

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

$$f = \sum_i \delta(\mathbf{R} - \mathbf{R}_i)\delta(v_\parallel - v_{\parallel,i})\delta(\mu - \mu_i)$$

- Gyrokinetic Equations

$$\frac{d\mathbf{R}}{dt} = \frac{1}{B^{\star\star}}\left[v_\parallel(\mathbf{B}^\star - \mathbf{b_0} \times (< \mathbf{E} > - \frac{1}{q}\mu\nabla(B_0 + < \delta B >))\right]$$

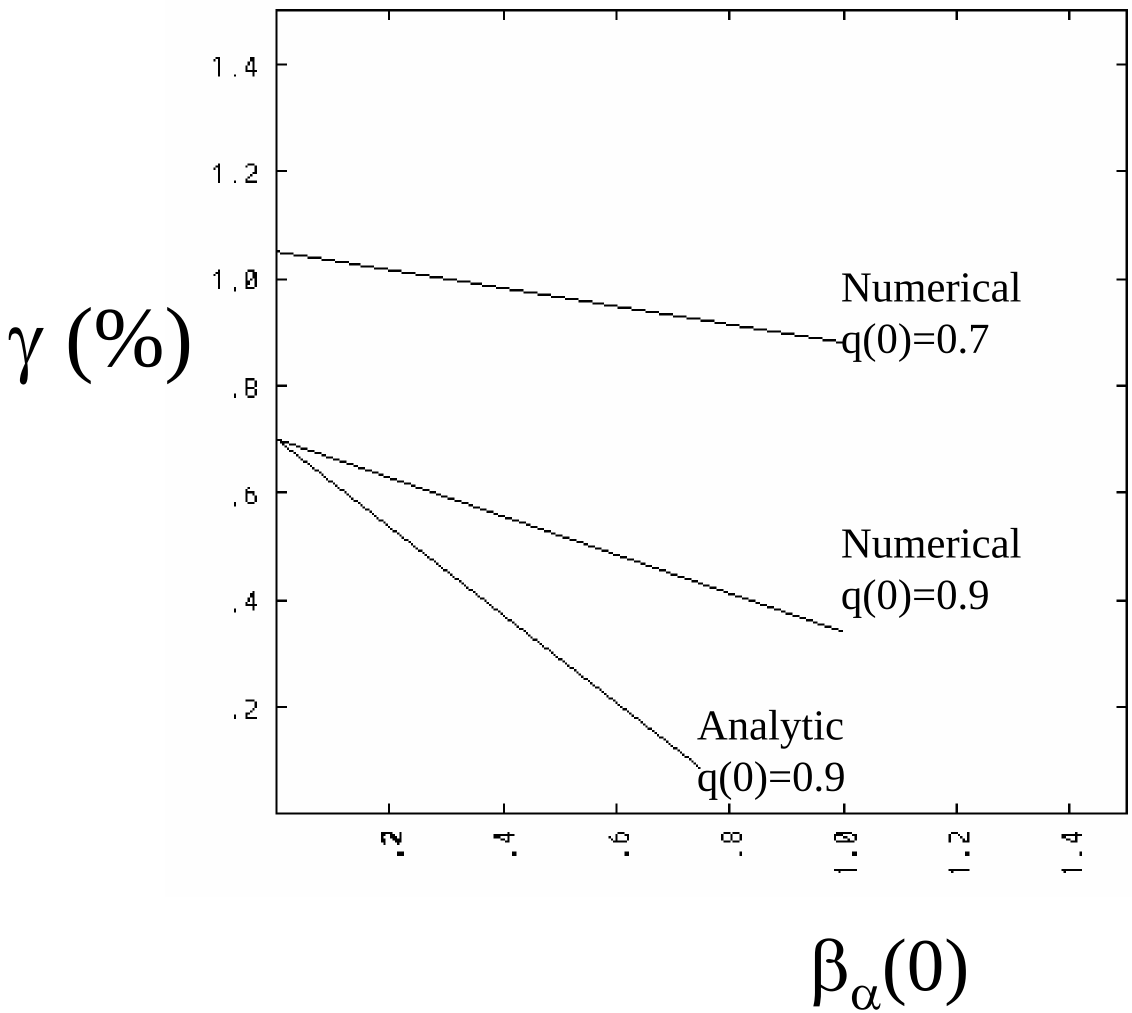
$$m\frac{dv_\parallel}{dt} = \frac{q}{B^{\star\star}}\mathbf{B}^\star \cdot (< \mathbf{E} > - \frac{1}{q}\mu\nabla(B_0 + < \delta B >))$$

$$\mathbf{B}^\star = \mathbf{B_0} + < \delta\mathbf{B} > + \frac{mv_\parallel}{q}\nabla \times \mathbf{b_0}, \qquad B^{\star\star} = \mathbf{B}^\star \cdot \mathbf{b_0}$$

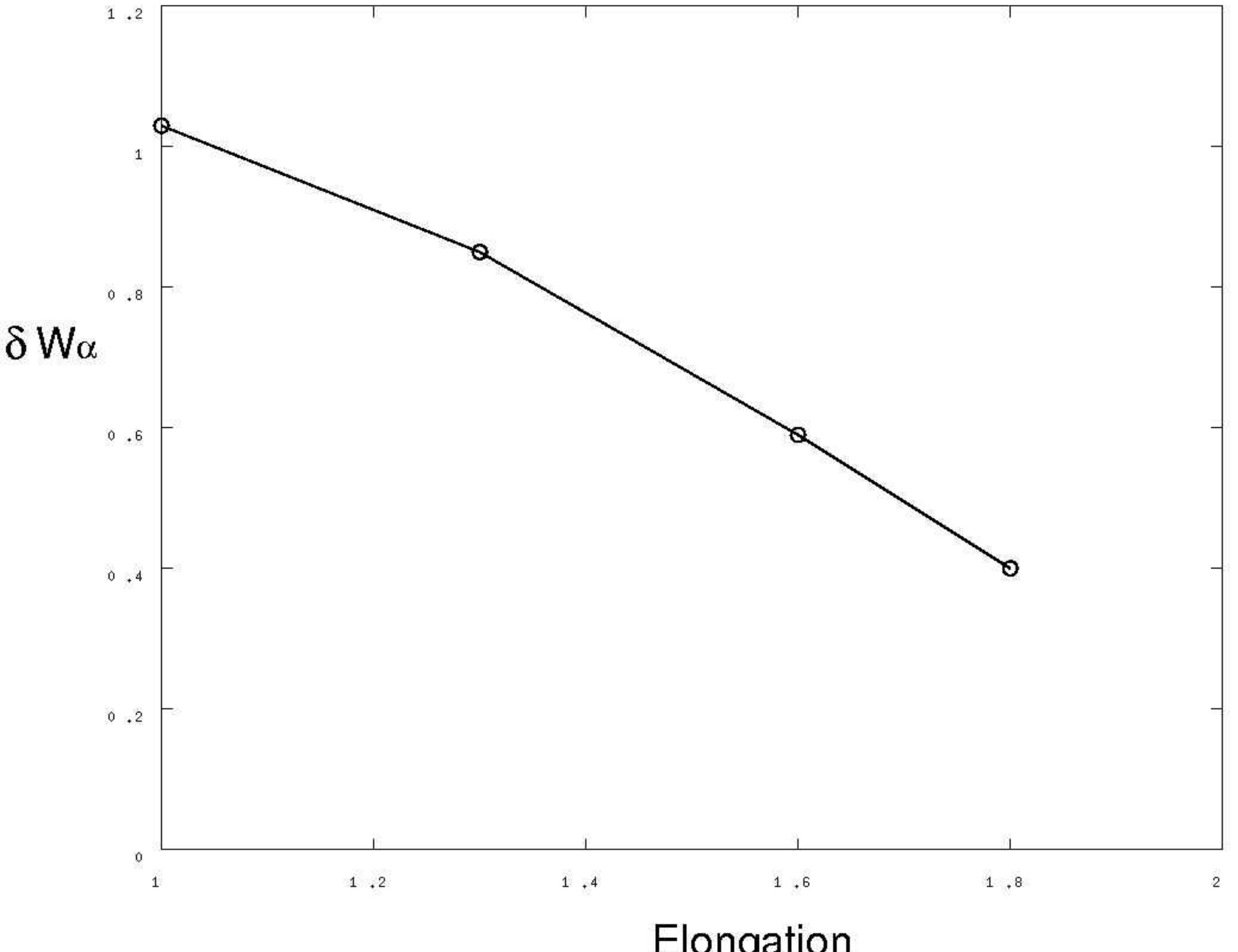
M3D code

- **M3D solves the extended MHD equation as an initial value problem (nonlinear !);**
- **It uses unstructured mesh in poloidal planes and finite difference in toroidal direction;**
- **The code runs on massively parallel machines such as Seaborg;**
- **The hybrid code has been benchmarked against NOVA-K code and NOVA2 code.**
- **The hybrid code has been used to study alpha particle stabilization of internal kink in ITER and nonlinear evolution of energetic particle-driven TAE modes (Fu, IAEA, 2004).**

Alpha Particle Stabilization of Internal Kink Mode for ITER: dependence on q(0)



Plasma shaping reduces alpha particle stabilization significantly



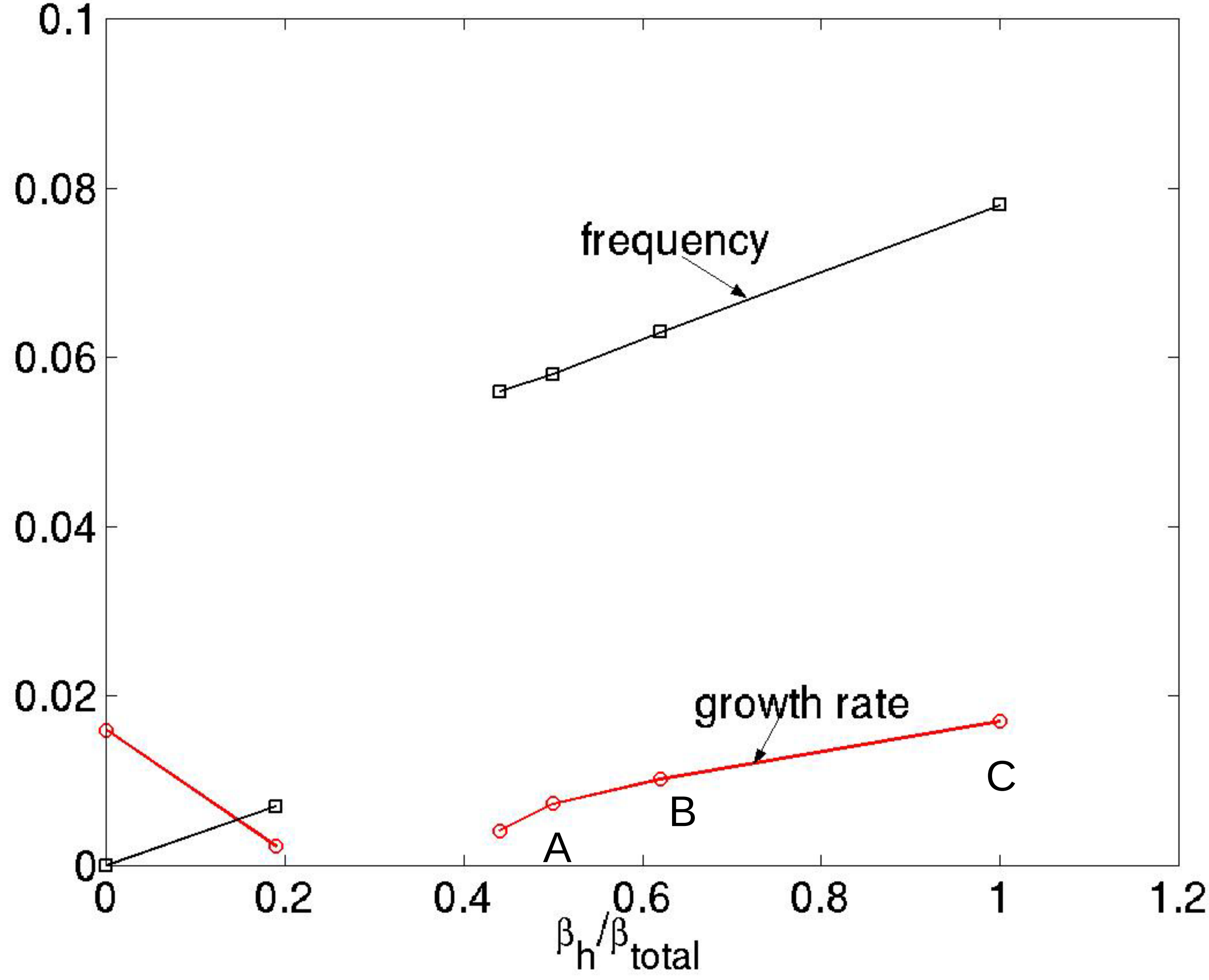
Linear Simulations of Fishbone

circular tokamak R/a=2.76
q(0)=0.9, q(a)=2.5
β_total(0) = 5.7% (fixed)

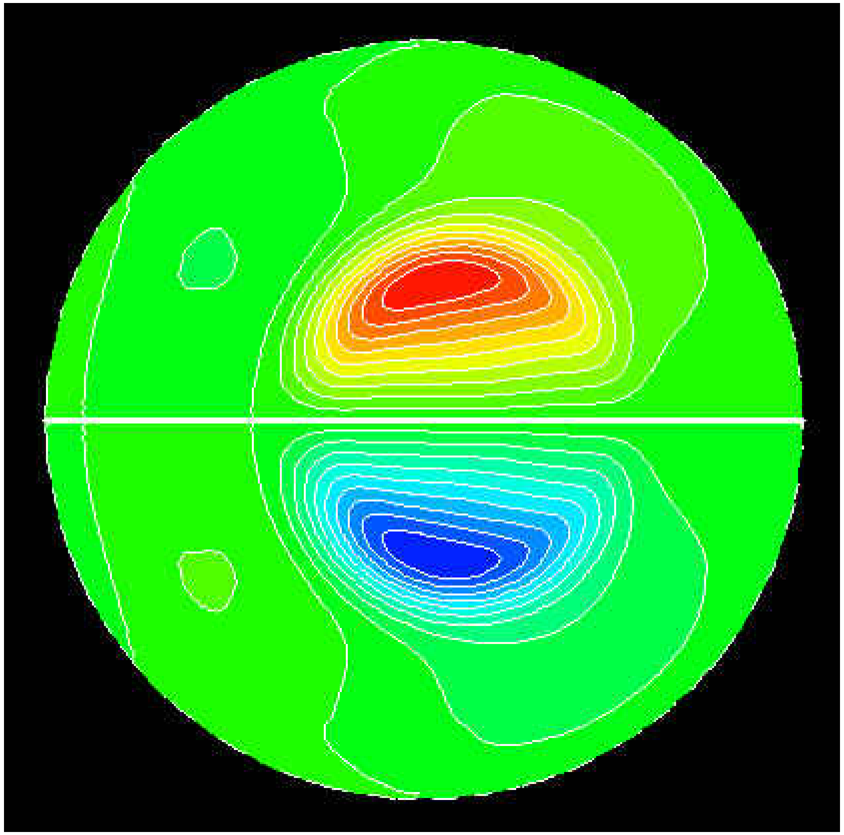
$p \sim p_h \sim \exp(-\psi/0.25)$

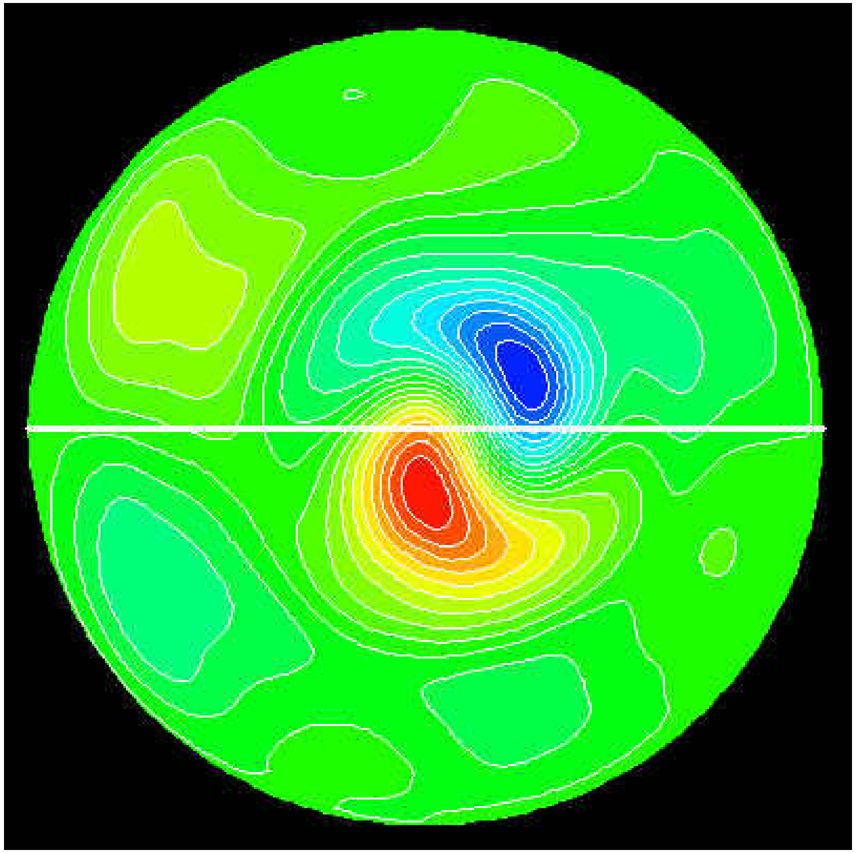
v_h/v_A = 1.0, ρ_h/a=0.10
Isotropic slowing-down energetic particle distribution

Excitation of Fishbone at high β_h



Mode Structure: Ideal Kink v.s. Fishbone



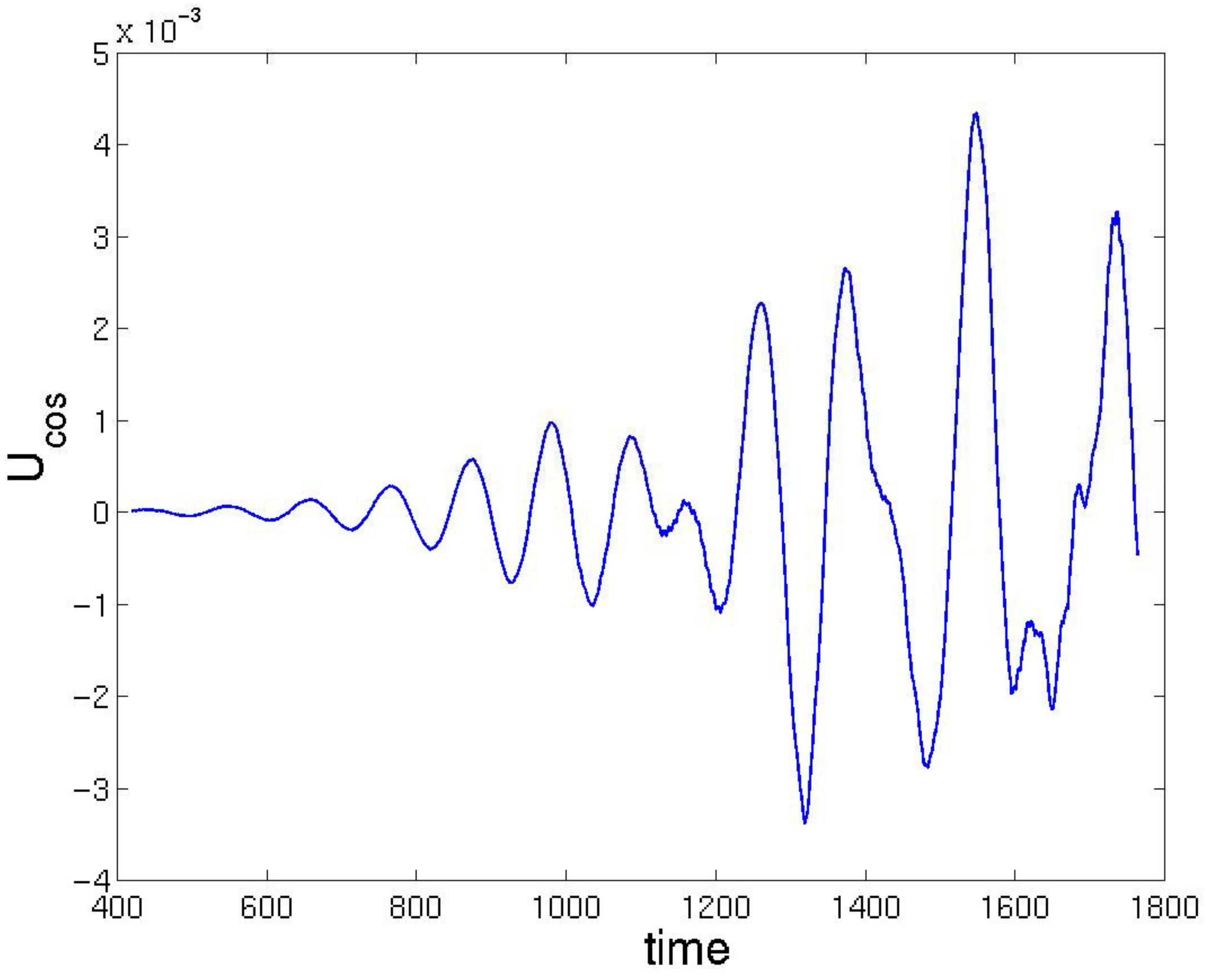


Nonlinear Simulations I: nonlinear particle and linear MHD

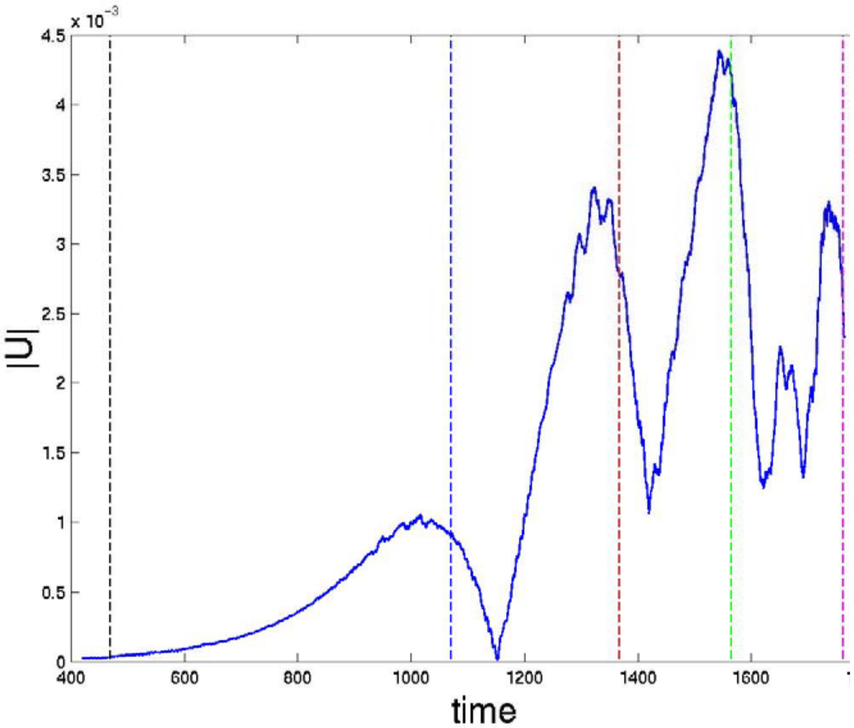
- **Case A: γ=0.007 ω=0.058**
- **Case B: γ=0.010 ω=0.063**
- **Case C: γ=0.017 ω=0.078**

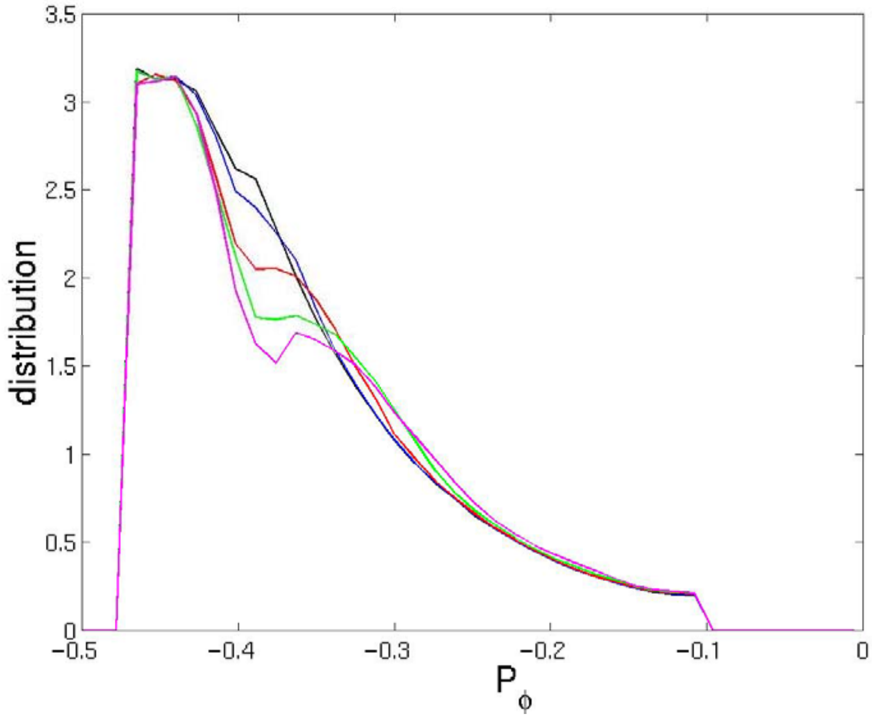
- **We investigate nonlinear evolution of fishbone mode due to self-consistent modification of particle distribution function.**

Nonlinear evolution of fishbone (case A, cos component of U)

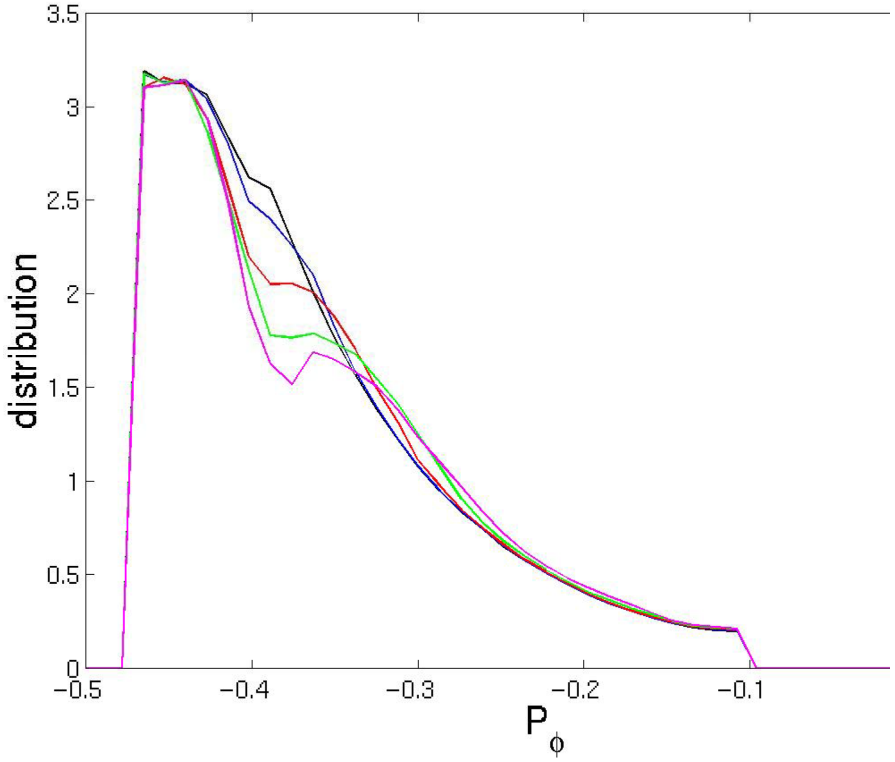


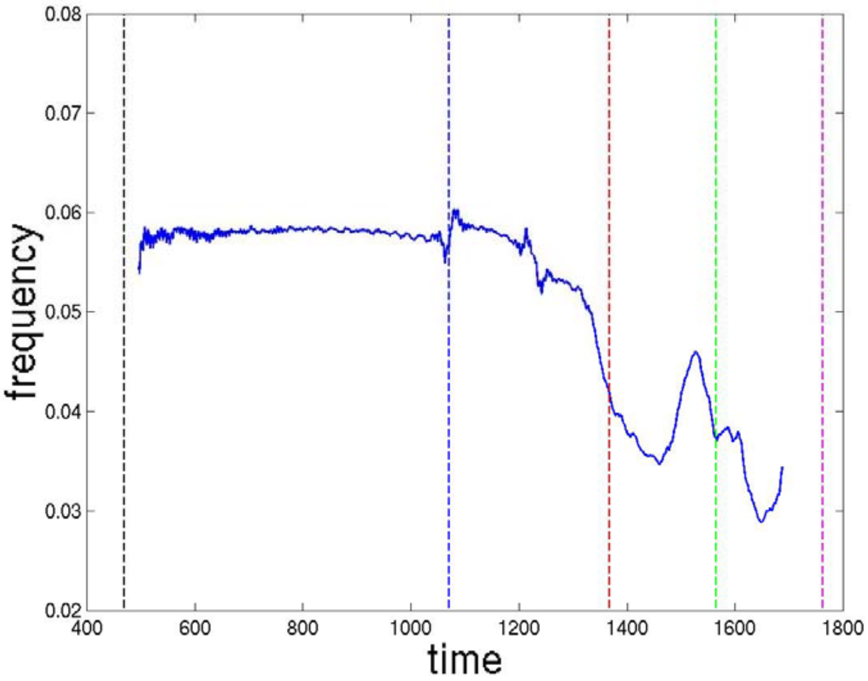
Particle distribution flattening causes mode saturation. However, enhancement in the neighboring gradient causes multiple amplitude peaks.



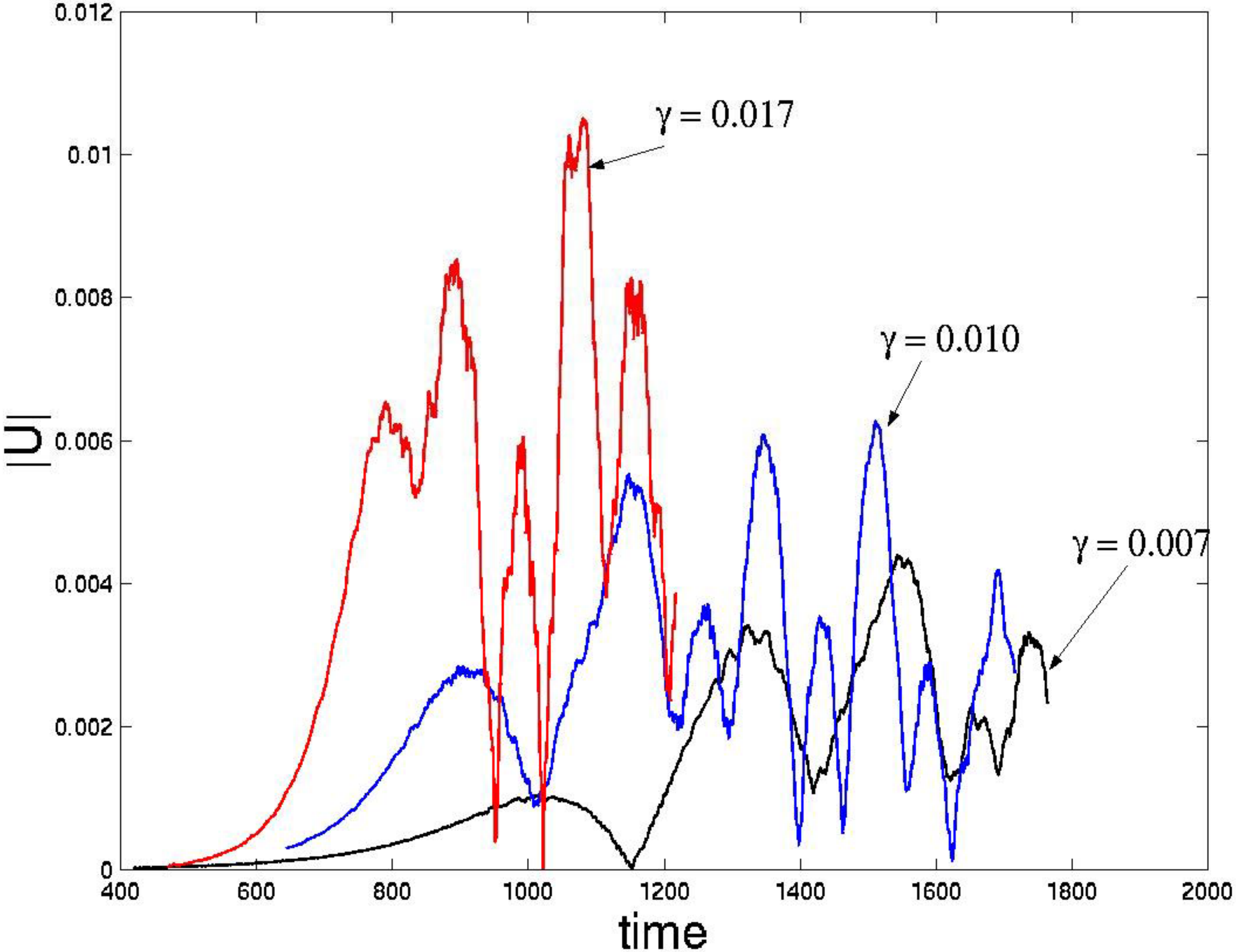


As flattening region of distribution increases, the mode frequency chirps down.





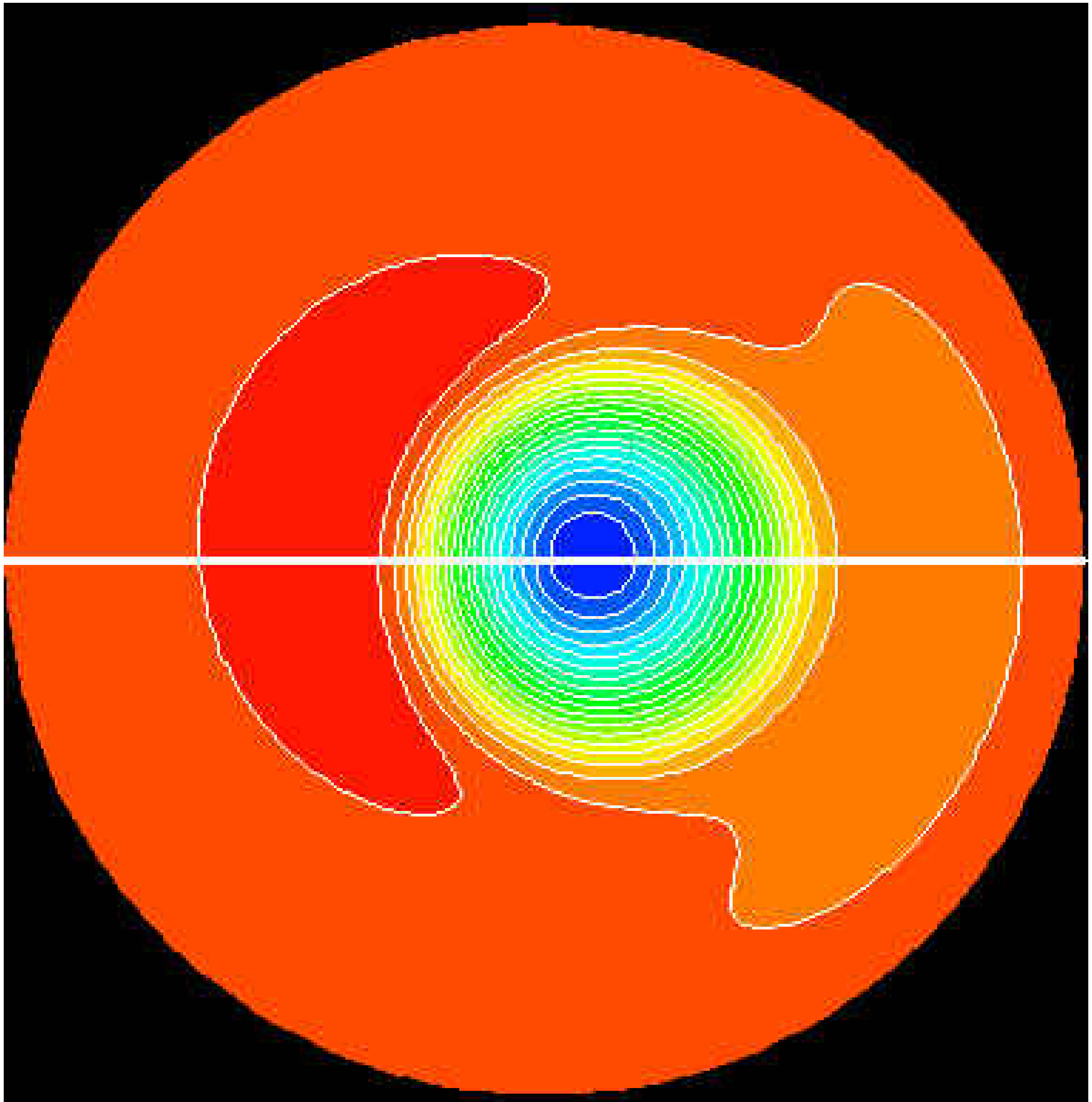
Saturation amplitude scales as linear growth rate.



Nonlinear Simulations of Fishbone II: nonlinear particle and nonlinear MHD

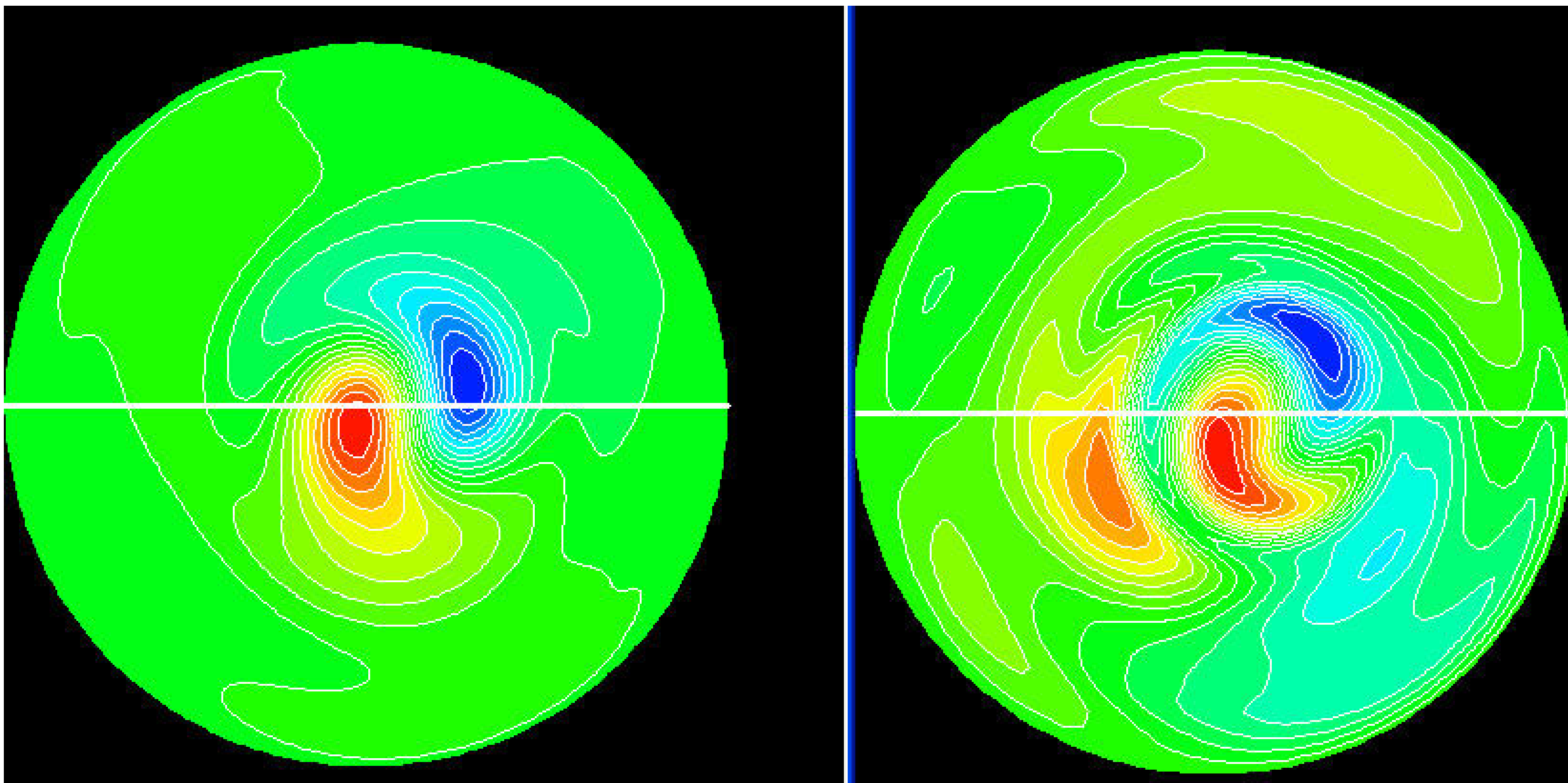
- **Investigate combined effects of MHD nonlinearity and particle nonlinearity;**
- **MHD nonlinearity is found to reduce saturation amplitude. The reduction is stronger for larger linear growth rate.**

Nonlinear generation of equilibrium flow

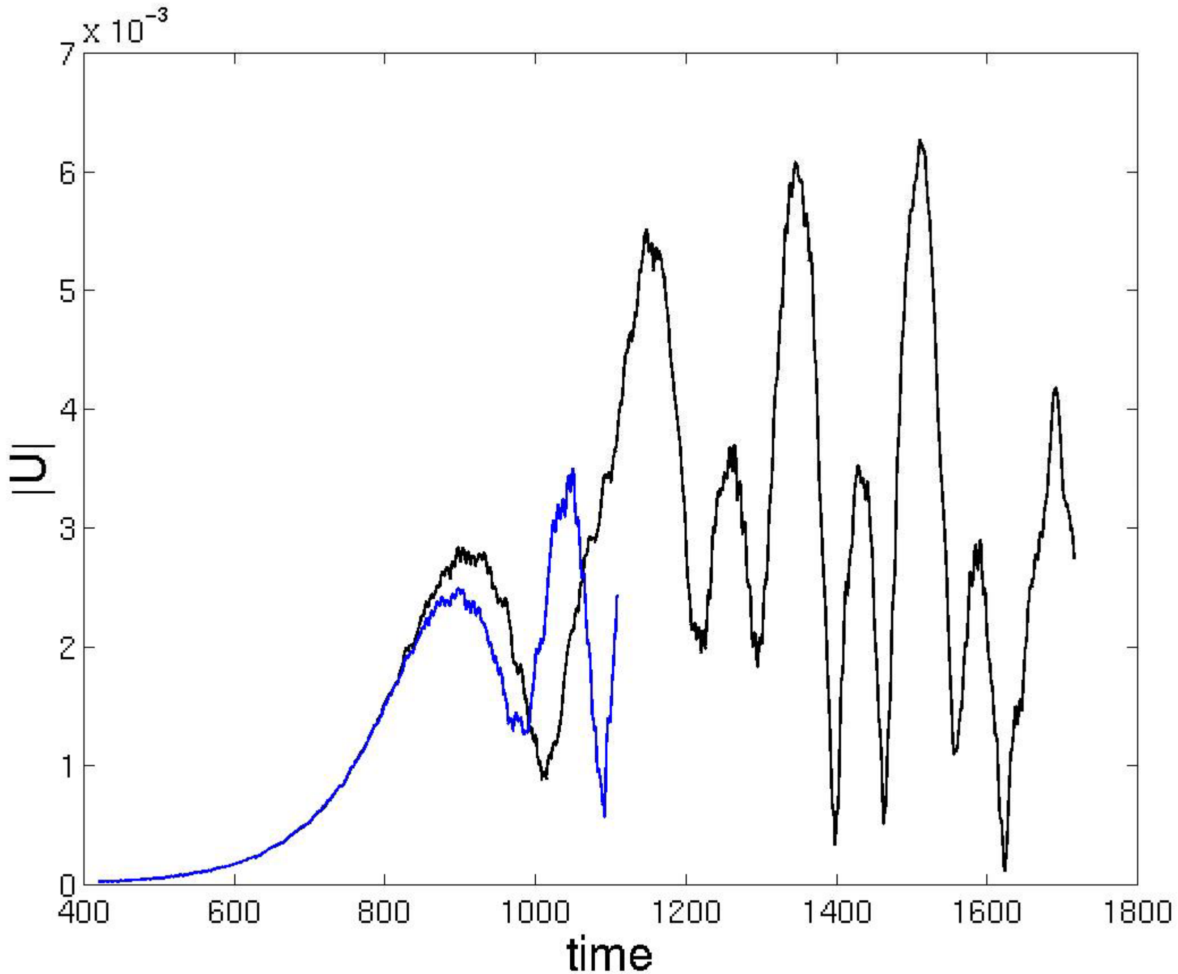


MHD nonlinearity changes mode structure significantly

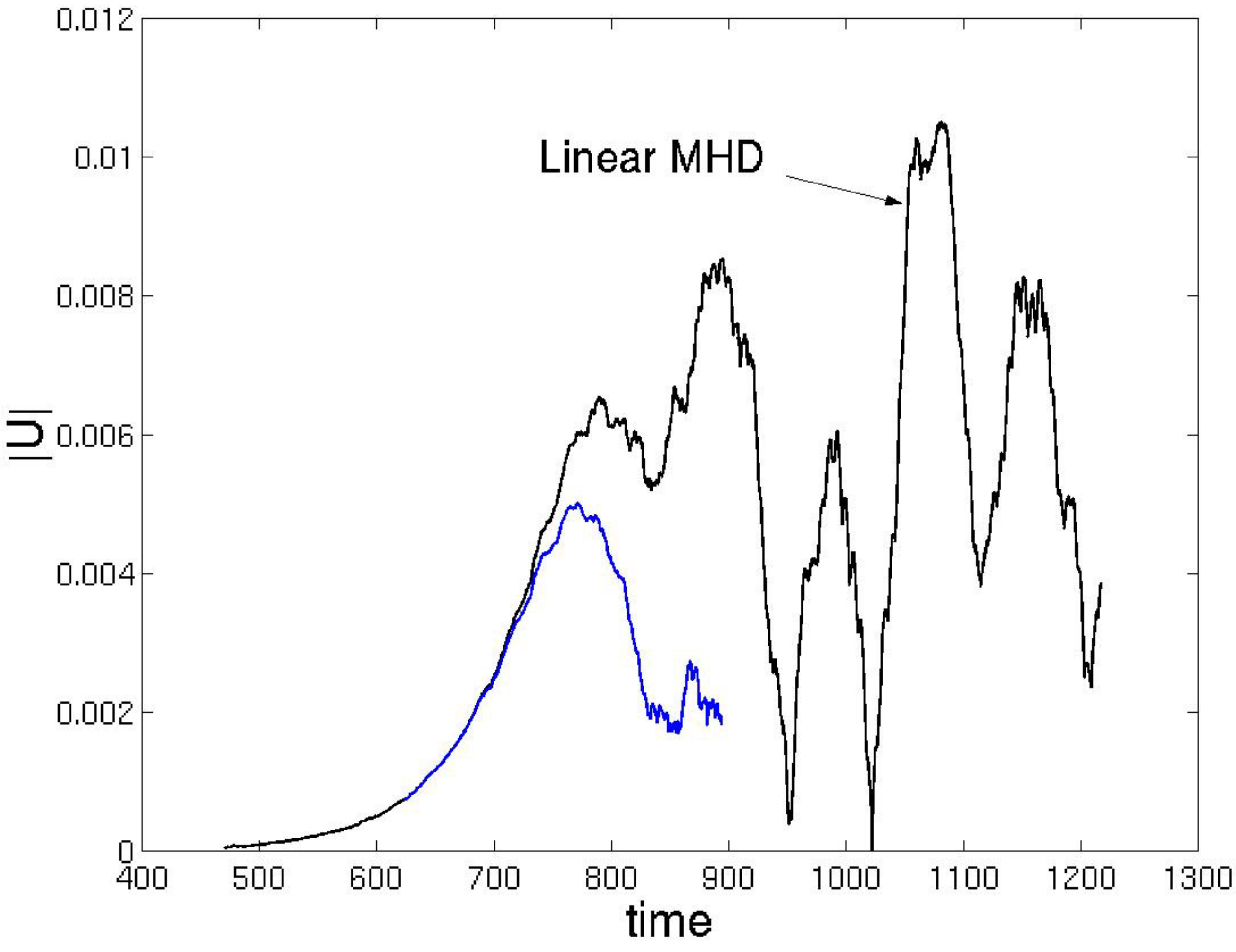
Linear MHD | **Nonlinear MHD**



MHD nonlinearity reduces mode saturation level (case B)



MHD nonlinearity reduces mode saturation level (case C)



Discussions

- Our model includes self-consistent mode structure and both MHD and kinetic nonlinearity.
- Strong chirping of fishbone can be explained by kinetic nonlinearity alone.
- However, MHD nonlinearity is essential to model full dynamics of bursting fishbone.
- For most cases studied, MHD nonlinearity is stabilizing and there is no initial destabilizing effects as found by Odblom et al. We believe this is due to finite viscosity used in our simulations.
- However, for few cases with small viscosity, there is some evidence of initial destabilizing due to MHD nonlinearity. Work is in progress to confirm this result and to assess how important it is for overall fishbone bursts.

Conclusions

- We have done a comprehensive simulation of fishbone instability in which both particle nonlinearity and MHD nonlinearity are included and mode structures are determined self-consistently.
- For linear MHD/nonlinear particle cases, strong frequency chirping is found together with flattening of particle distribution function. (consistent with work of Berk-Breizman). The self-consistent evolution of mode structure appears to be important.
- For full nonlinear cases, MHD nonlinearity does not enhance the initial linear growth rate, perhaps due to large radial width of the mode. However, MHD nonlinearity reduces the initial saturation level significantly, especially for large linear growth rates.

M3D agrees with NOVA2 code