Particle Closure for Simulating Kinetic Effects On MHD Modes

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Outline

- Introduction
- Hybrid model for energetic particles
- Highlights of M3D Hybrid Simulations
- Gyrokinetic model for MHD ?

Introduction

- MHD modes:

kink, ballooning, tearing, Alfven waves

- Kinetic effects:

Trapped particle stabilization of kink and ballooning modes;

Energetic particle destabilization of Alfven waves;

FLR and drift effects etc.

Types of kinetic model

Fluid closure

Particle-based closure

PIC/continuum model

Particle closure for energetic particles and thermal ions

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

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

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

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

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

CGL pressure and gyrokinetic equations

- Pressure tensor

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

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

- Gyrokinetic Equations

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

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

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

Highlights of Recent M3D Hybrid Simulations

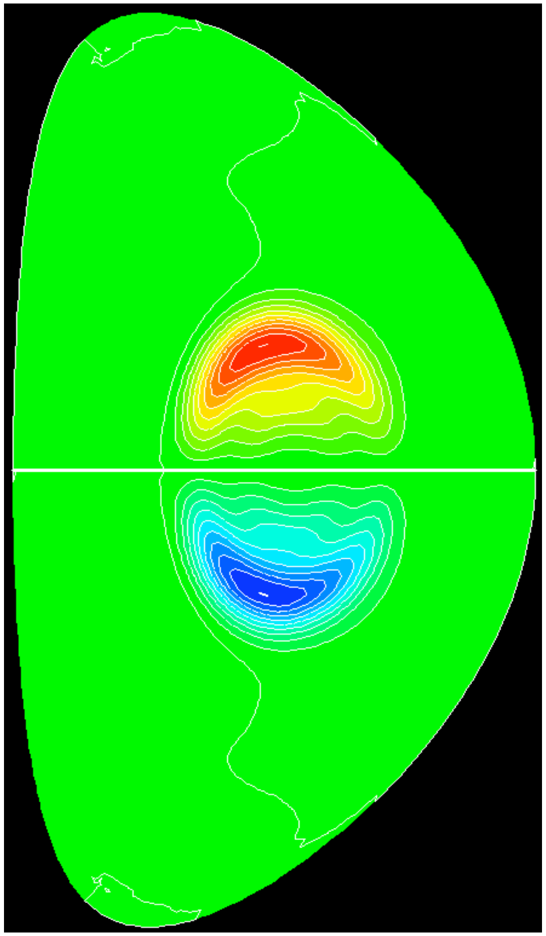
- M3D results agree with NOVA2 code;
- Results of ITER simulations show importance of shaping on alpha particle stabilization of internal kink;
- Simulations of beam-driven Alfven modes show frequency chirping down as mode moving out radially;
- Simulations of fishbone instability show strong frequency chirping with large flattening region of particle distribution.

Ref: W. Park et al, Phys. Plasmas 1999.
G.Y. Fu et al., IAEA Fusion Energy Conference, 2004.
H.R. Strauss et al, Nucl. Fusion 44, 1008 (2004).
G.Y. Fu et al., submitted to Phys. Plasma, 2005.

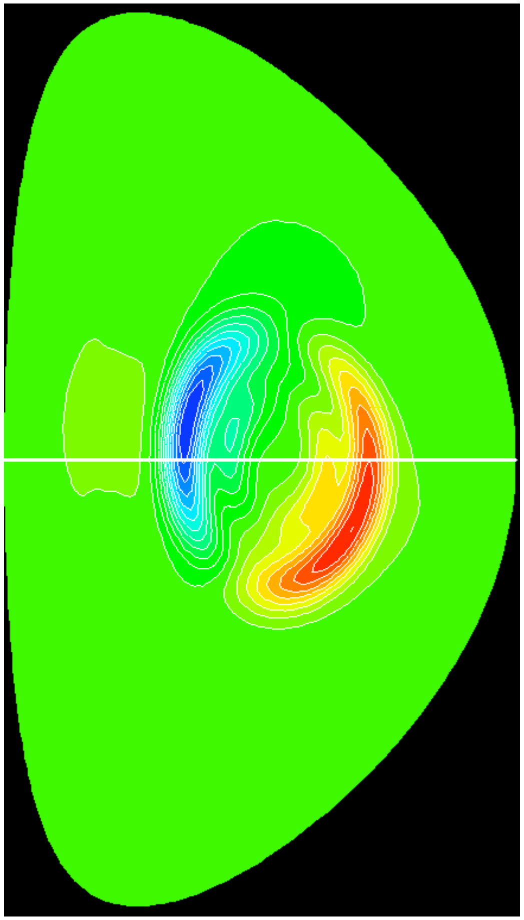
Alpha Particle Stabilization of Internal Kink Mode for ITER:

Internal Kink Mode Structure

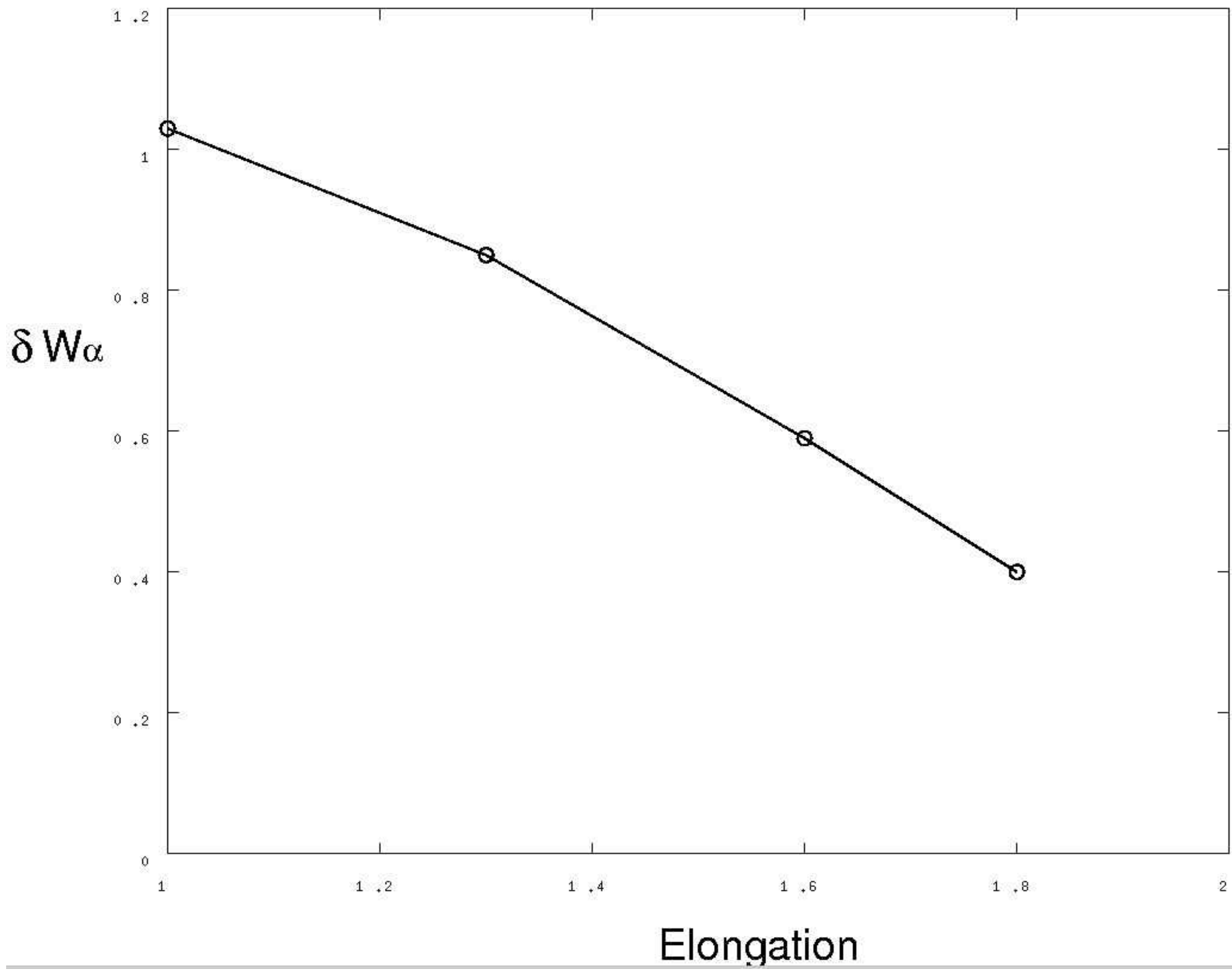
β_α=0.0



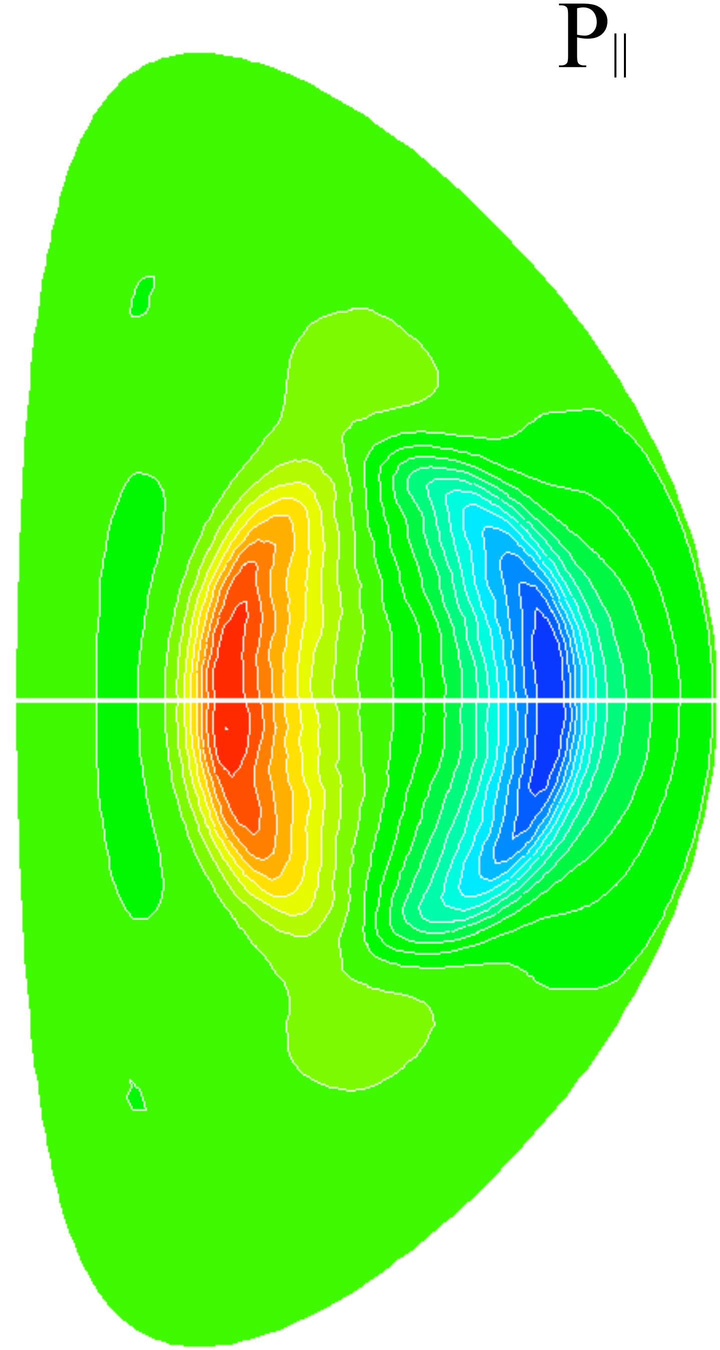
β_α=1.0%



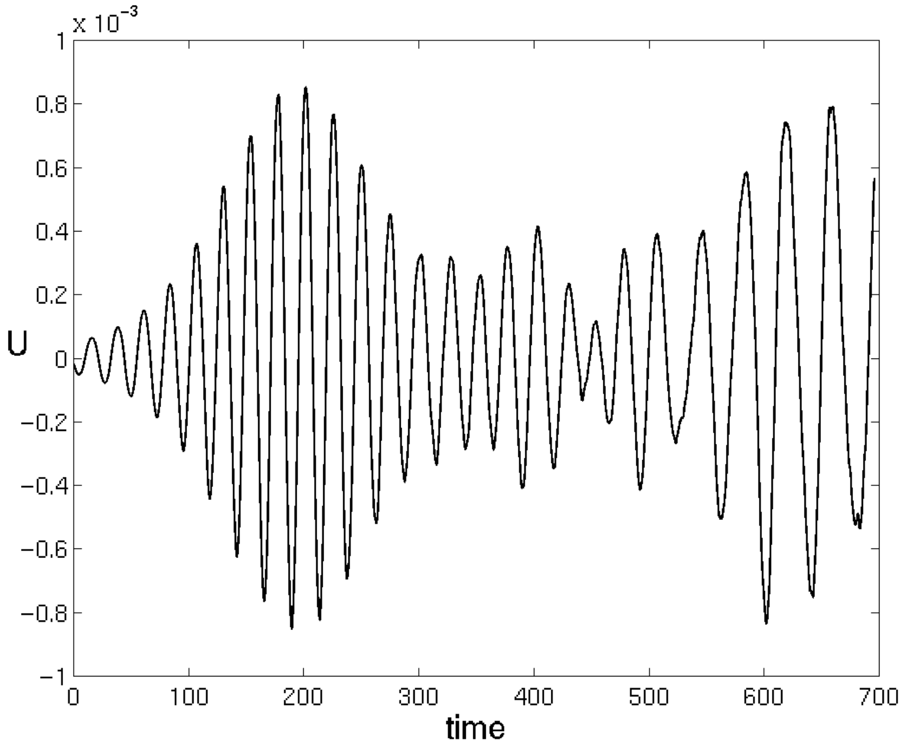
Plasma shaping reduces alpha particle stabilization significantly

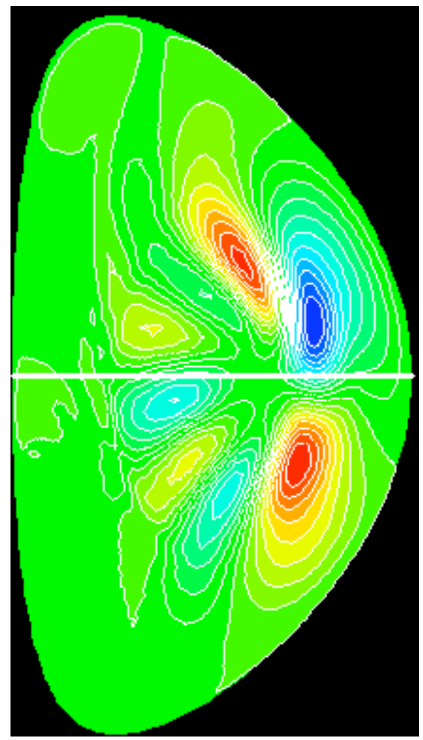


Thermal ion kinetic effects reduce MHD growth rate by half (Kruskal-Oberman)

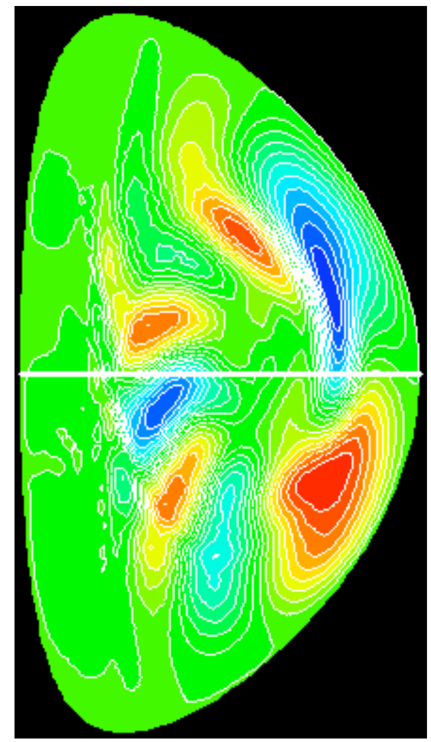


Beam-driven modes in NSTX



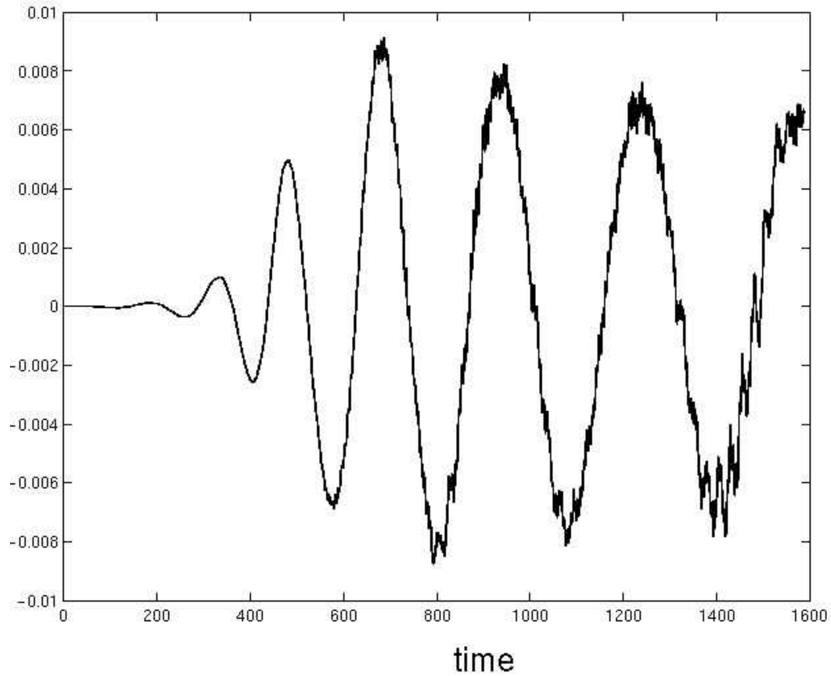


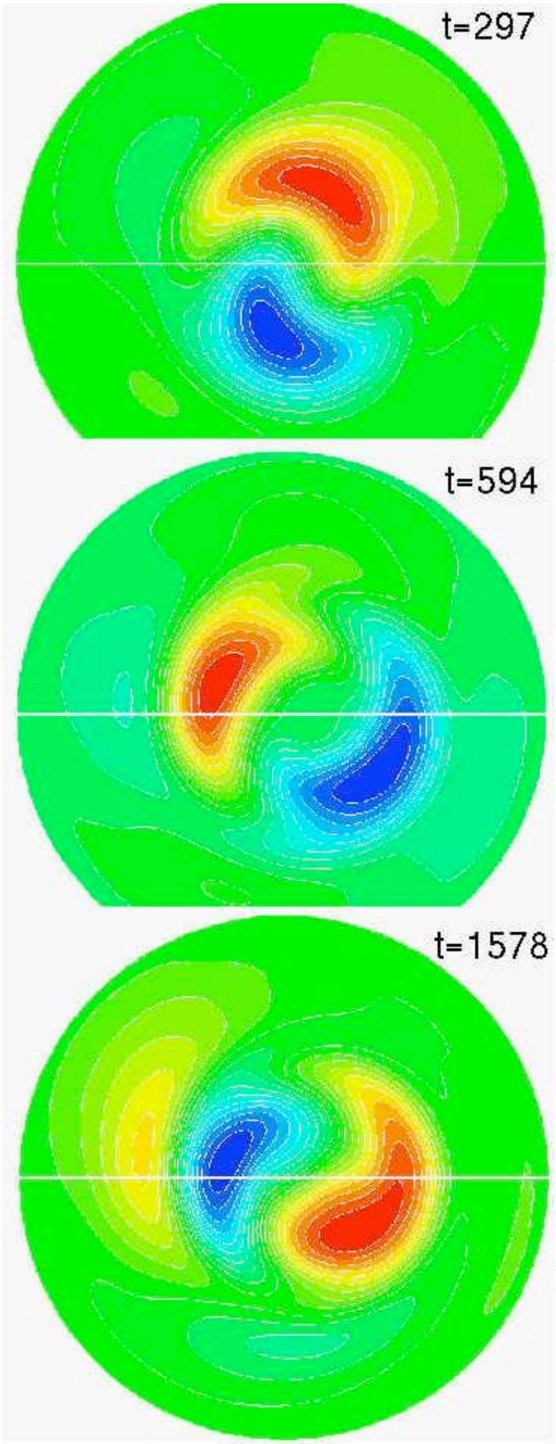
t=0.0



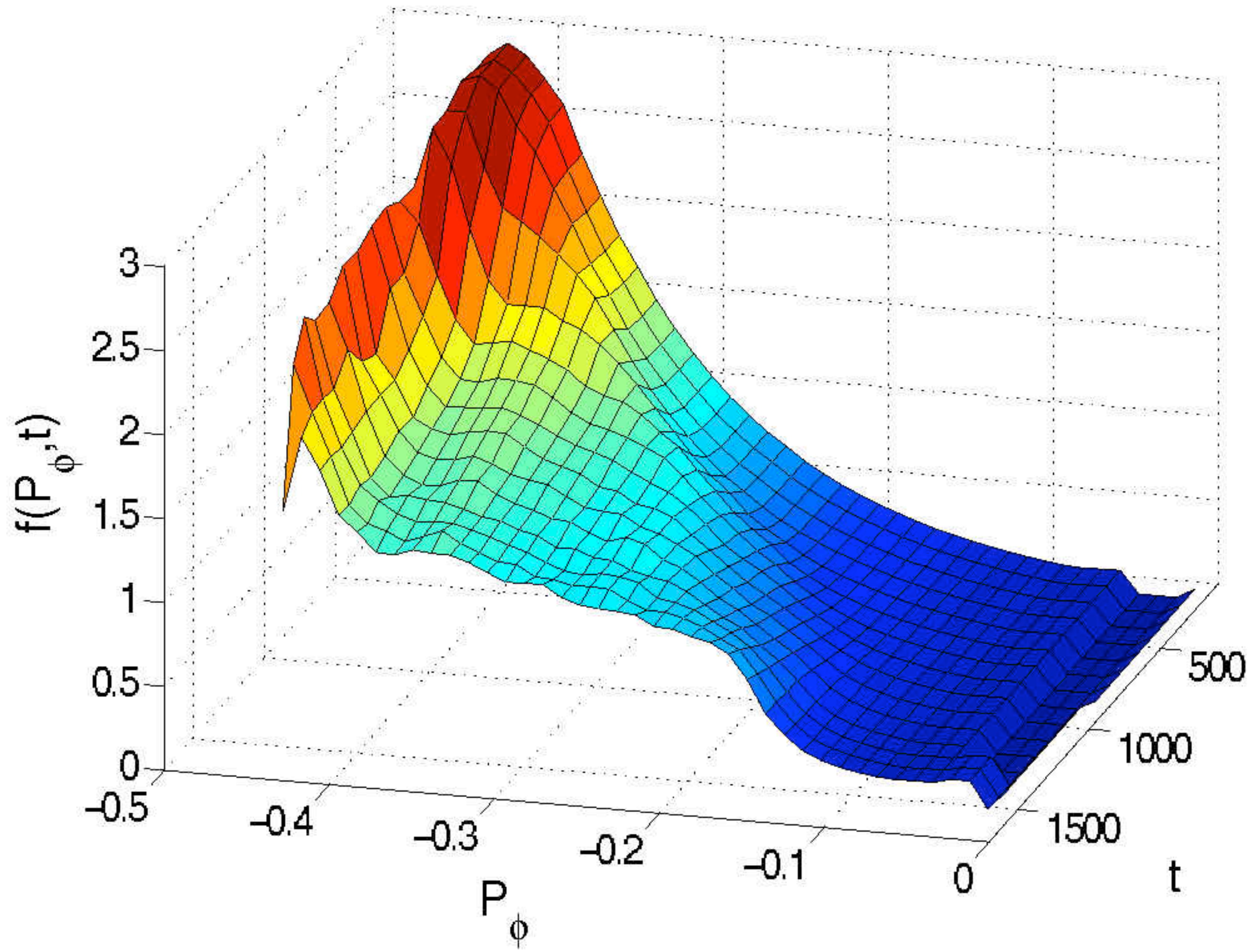
t=336

Nonlinear evolution of fishbone instability





Distribution evolution



Gyrokinetic model for MHD ?

- Linearized drift-kinetic eqns for each species

$$\frac{\partial \delta f}{\partial t} + (v_\parallel \mathbf{b} + \mathbf{v}_D)\cdot\nabla\delta f = -(\mathbf{v}_E + v_\parallel \frac{\delta \mathbf{B}_\perp}{B})\cdot\nabla f_0 - \dot{\varepsilon}\frac{\partial f_0}{\partial \varepsilon}$$

- Quasi-neutrality condition and Ampere's law

$$\frac{1}{\Lambda_D}(1-\Gamma_0(b))\phi = \frac{e}{\epsilon_0}(\delta\bar{n}_i - \delta n_e)$$

$$-\nabla_\perp^2 A_\parallel = \mu_0 j_\parallel$$

- Take moment of GK eqn and sum over species

$$\frac{\partial}{\partial t}e(\delta n_i - \delta n_e) = -\mathbf{b}\cdot\nabla j_\parallel - \int d^3\mathbf{v}\ e_j \mathbf{v}_{\mathrm{Dj}}\cdot\nabla\delta f_j$$

- Combined with field equations, and assuming $E_\parallel = \nabla_\parallel\phi - \frac{\partial A_\parallel}{\partial t} = 0$

$$\frac{\partial^2}{\partial t^2}\frac{1}{v_A^2}\nabla_\perp^2\phi = \mathbf{b}\cdot\nabla\nabla_\perp^2\mathbf{b}\cdot\nabla\phi + \frac{\partial}{\partial t}\int d^3\mathbf{v}\ e_j\mathbf{v}_{\mathrm{Dj}}\cdot\nabla\delta f_j$$

- This equation describes TAE (Fu and Van Dam, PFB 1, 1949(1989))