Integrated Simulations of Energetic Particle-driven Modes in Burning Plasmas

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Outline

- Hybrid model of M3D
- Highlights of M3D Hybrid Simulations
- Issues for integrated simulation of energetic particle-driven modes in burning plasmas

M3D XMHD Model

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

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

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

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

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

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

CGL pressure and gyrokinetic equations

- Pressure tensor

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

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

- Gyrokinetic Equations

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

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

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

Highlights of Recent M3D Hybrid Simulations

- n=1 mode in ITER;
- Fishbone nonlinear evolution in tokamak;
- Beam-driven Alfven modes in NSTX;

Ref: 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., Phys. Plasma 13, 052517, 2006.

n=1 mode in ITER

Importance of shaping effects on alpha particle stabilization of internal kink;

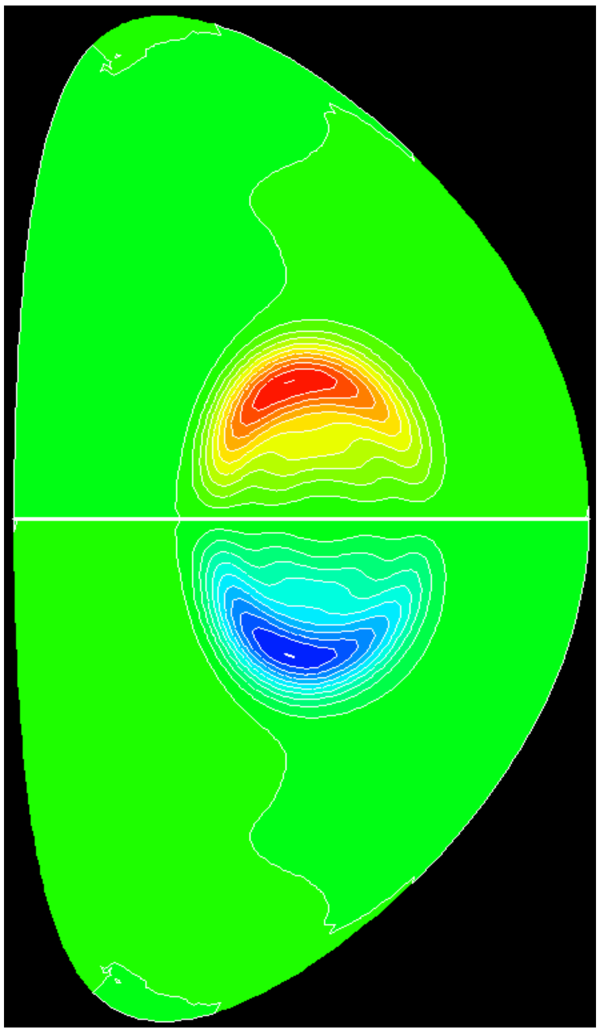
fishbone stability is marginal;

Ion kinetic effects are strongly stabilizing.

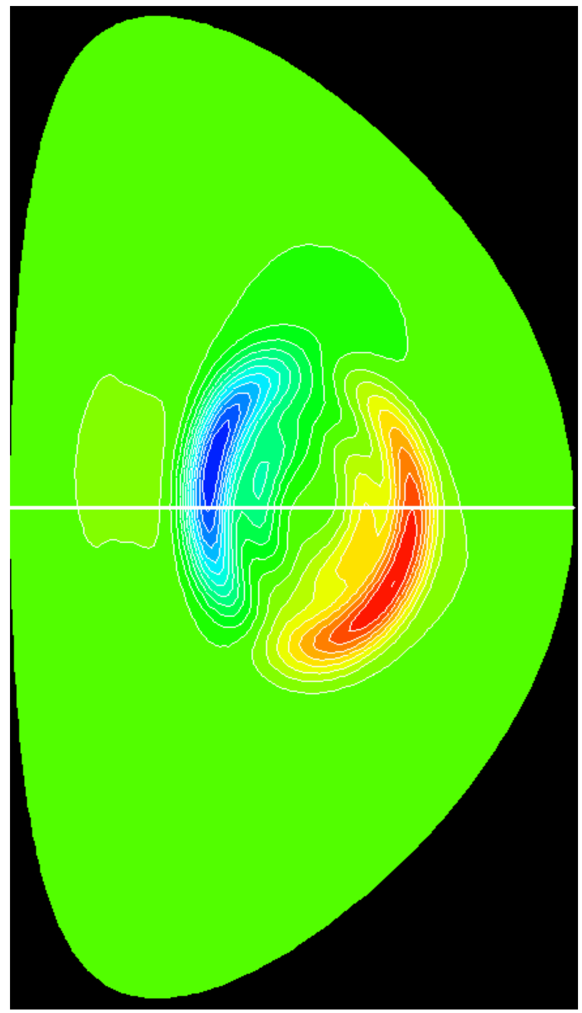
Alpha Particle Stabilization of Internal Kink Mode for ITER:

Internal Kink Mode Structure

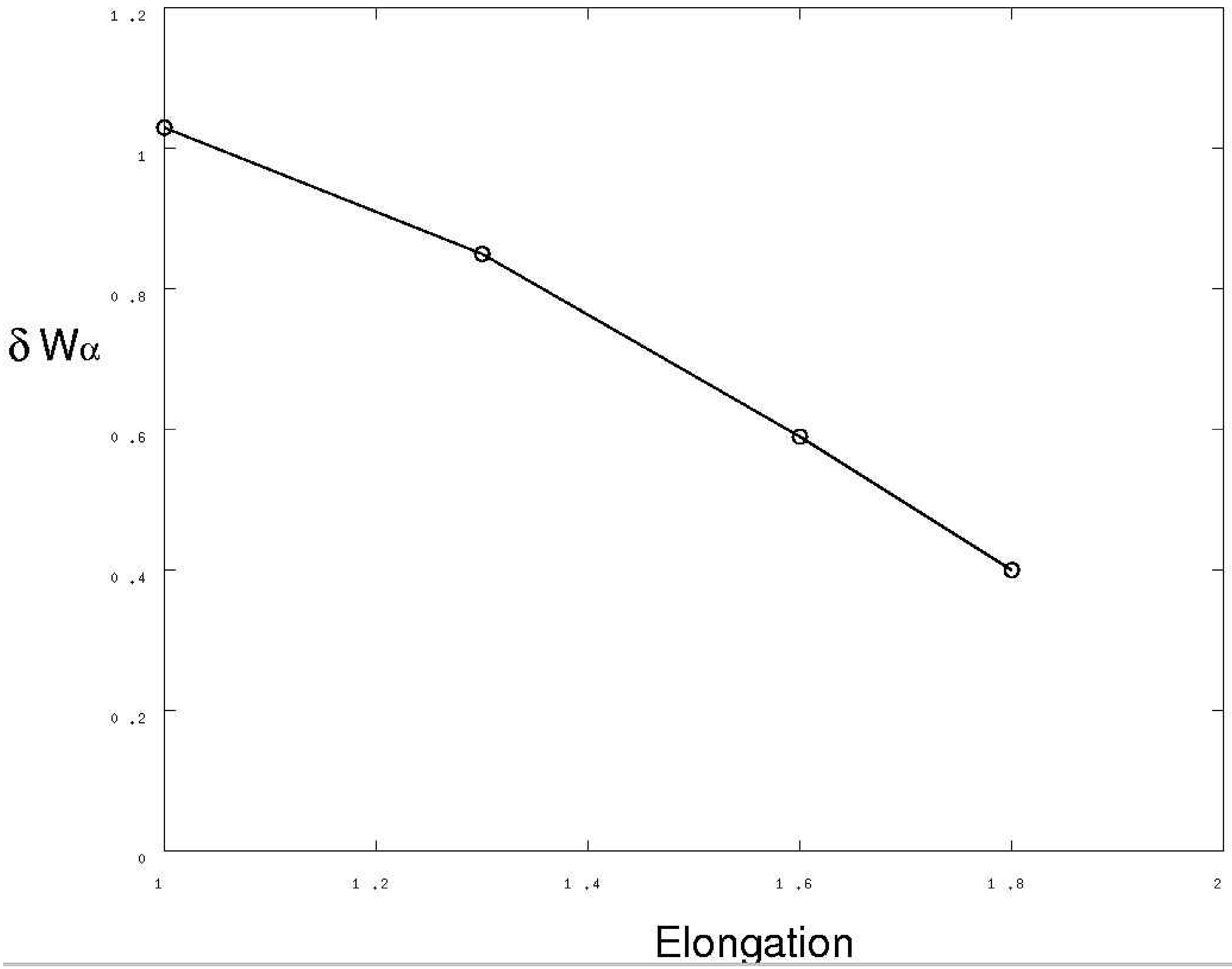
β_α=0.0



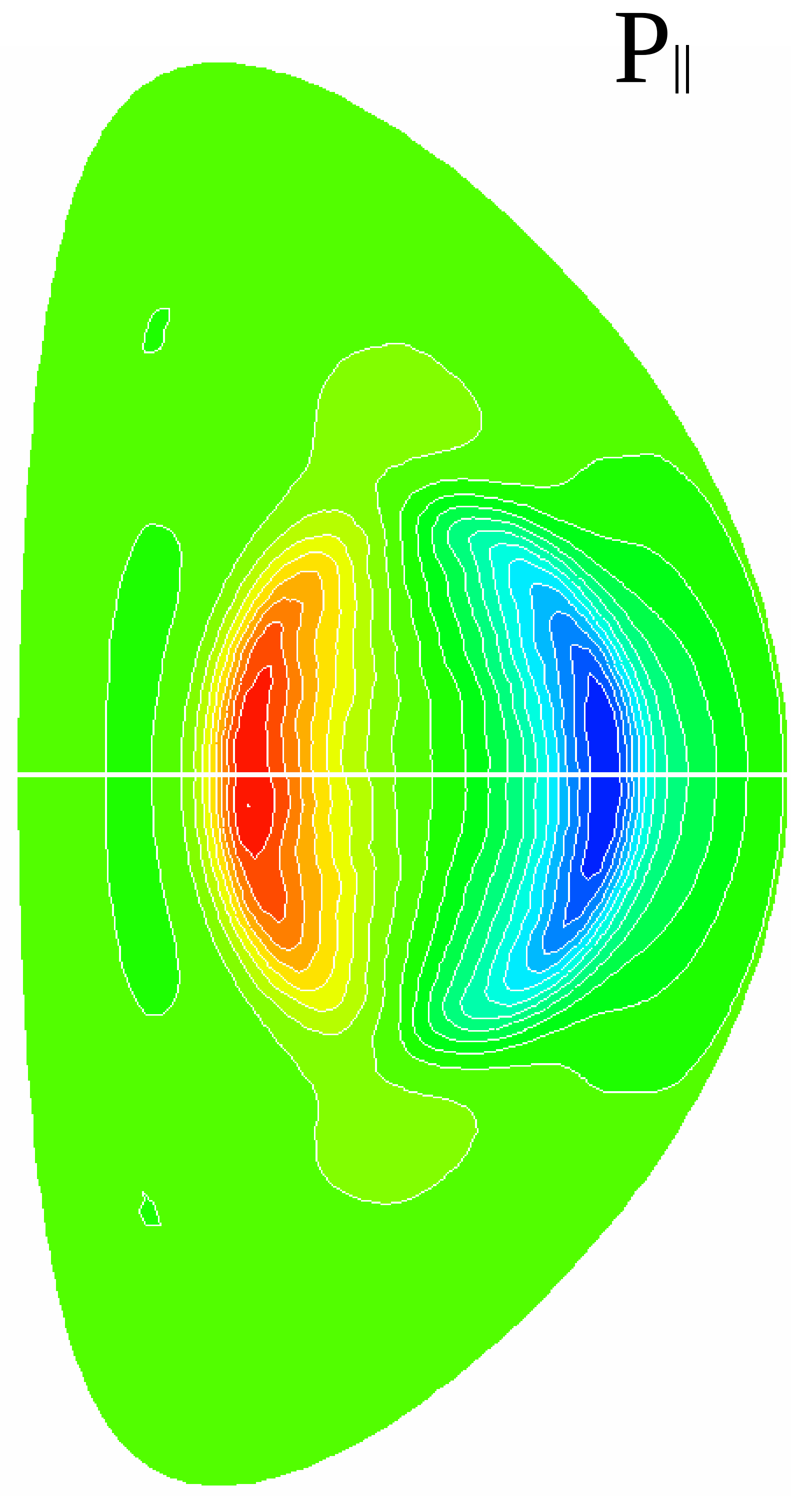
β_α=1.0%



Plasma shaping reduces alpha particle stabilization significantly



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



Beam-driven Alfven modes in NSTX

- TAE frequency chirping
- Multi-mode simulations show significant effects from mode-mode coupling;

Beam-driven modes in NSTX: frequency chirping

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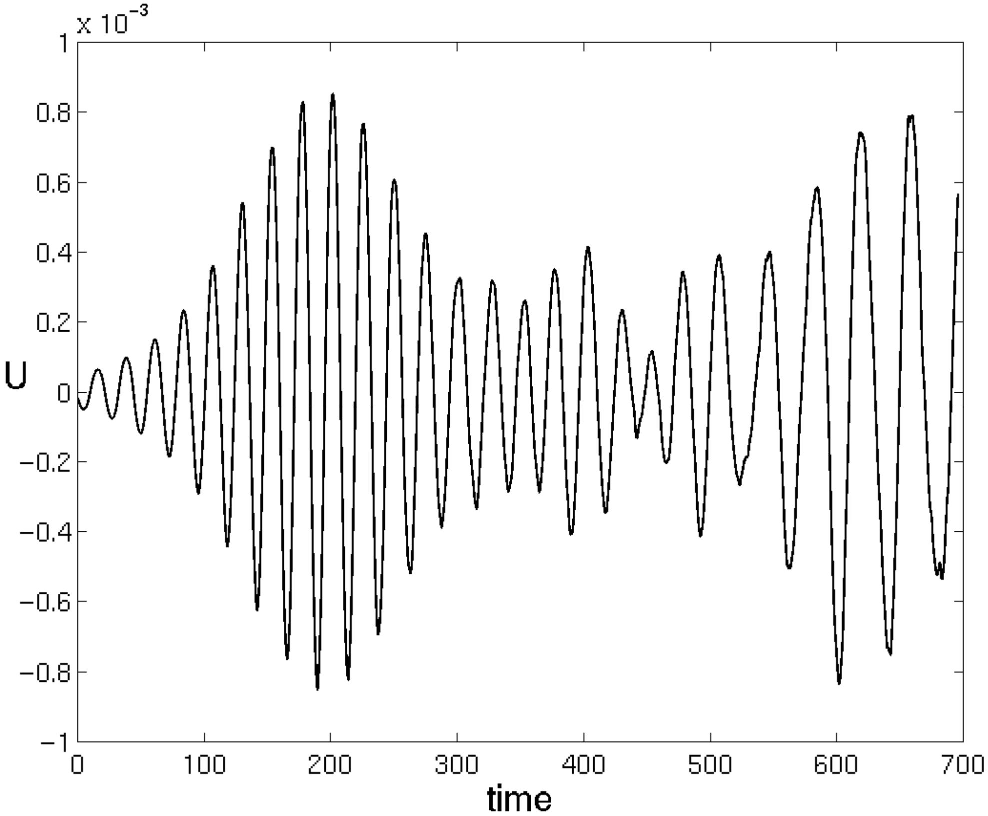
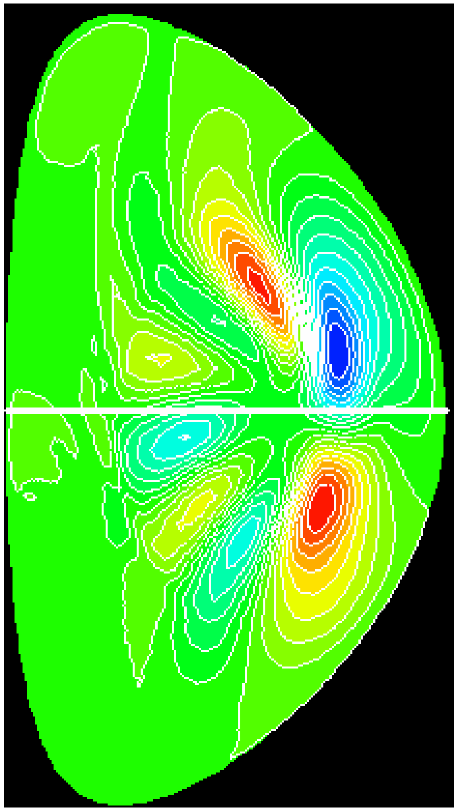
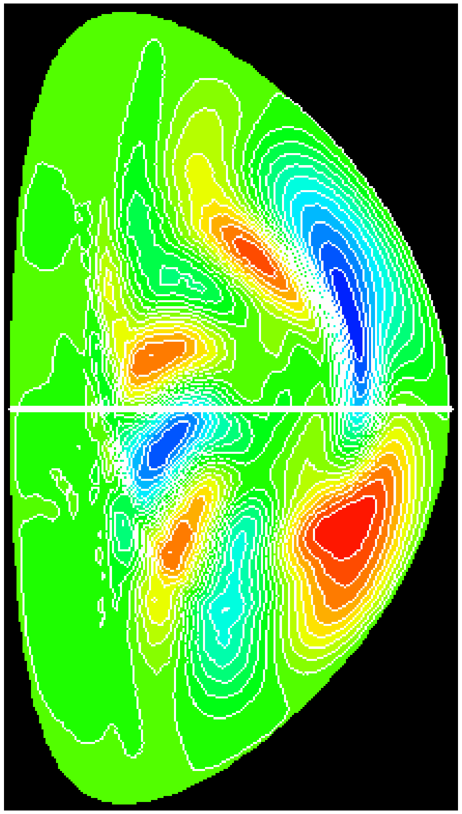


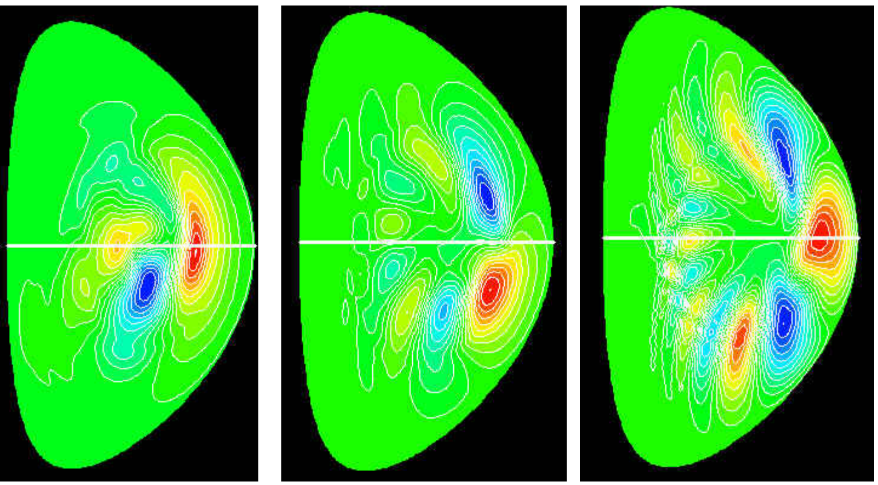


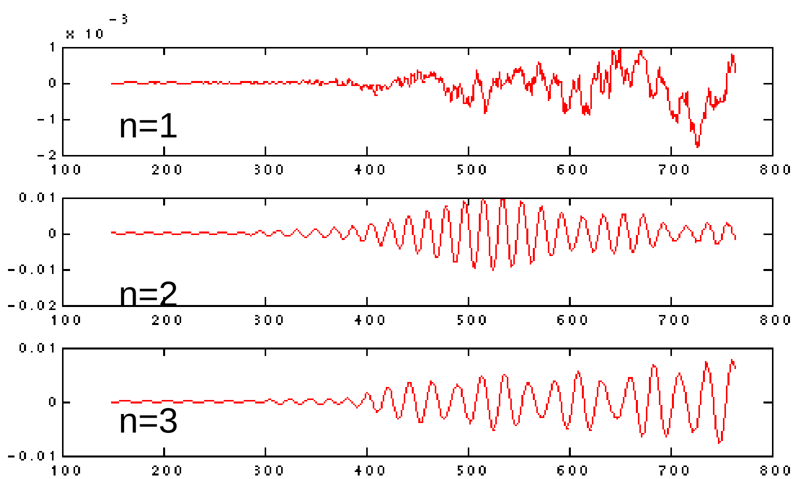


t=0.0 t=336

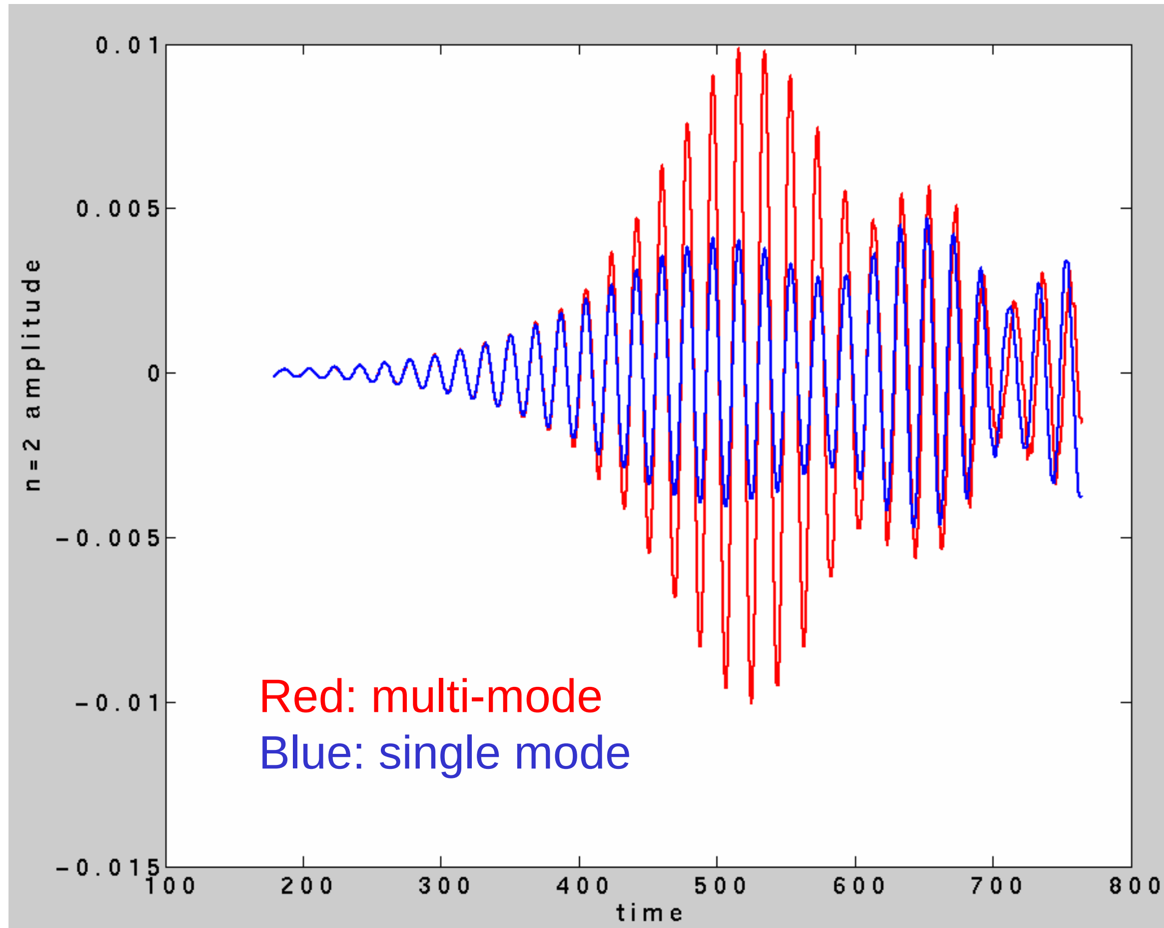
Multi-mode simulations of beam-driven Alfven modes show strong interaction between different toroidal modes

n=1 n=2 n=3

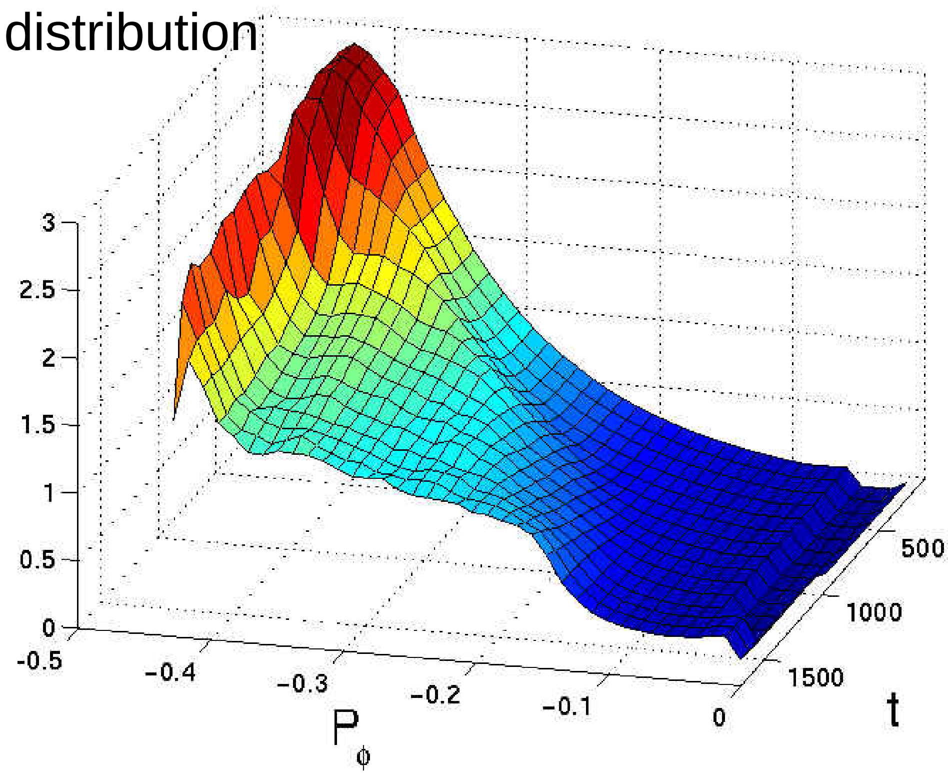


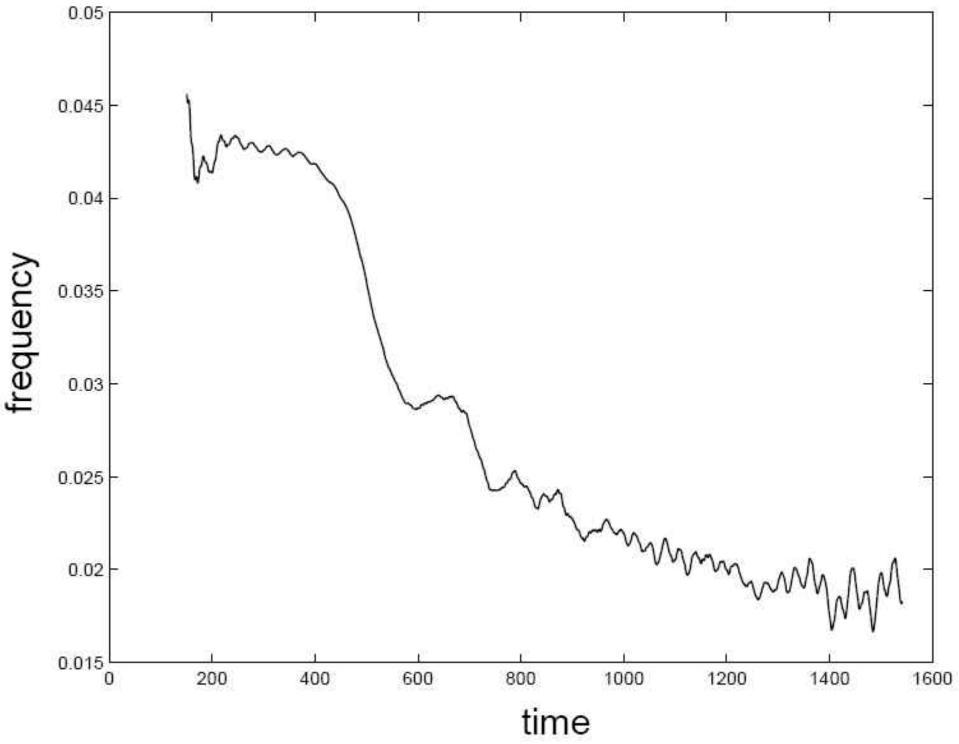


time

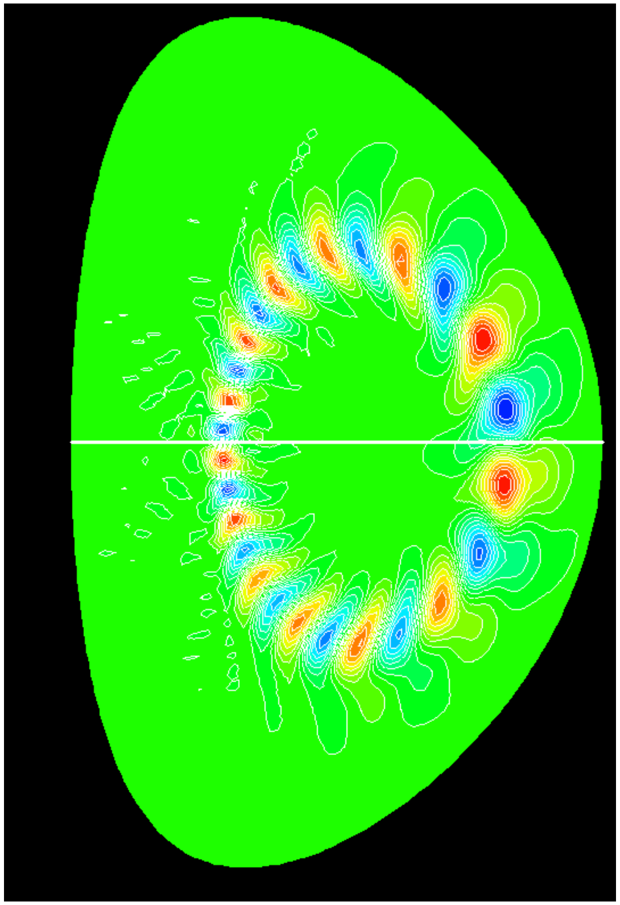


Simulation of fishbone shows distribution fattening and strong frequency chirping

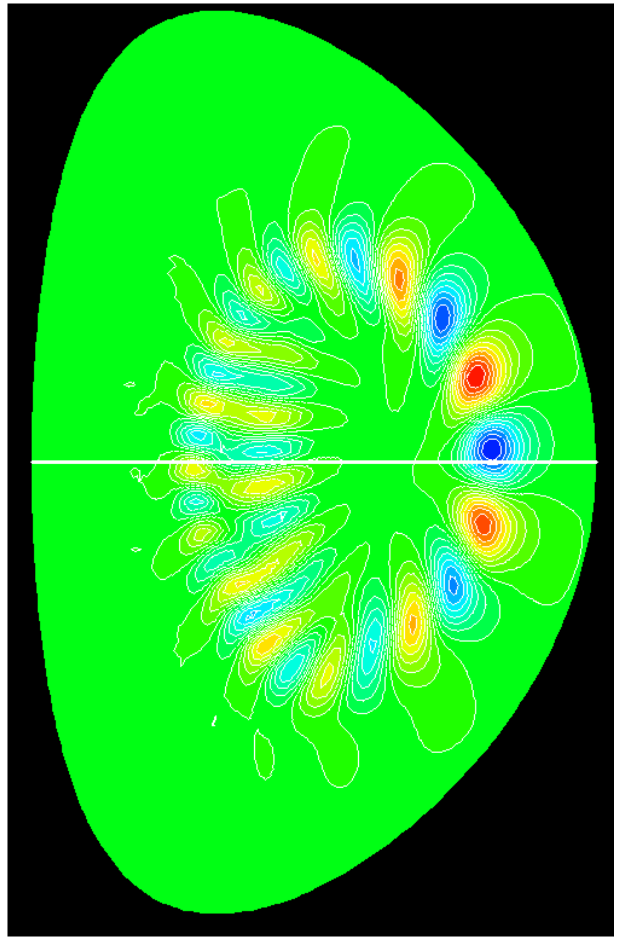




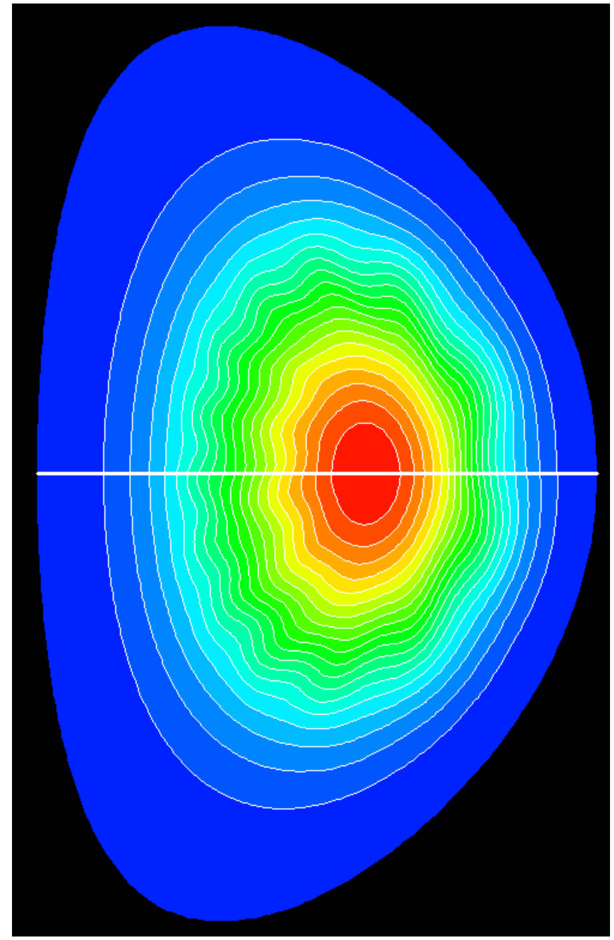
Initial simulations of Alfven eigenmodes in reversed shear DIIID plasmas



Velocity stream function



Pressure perturbation

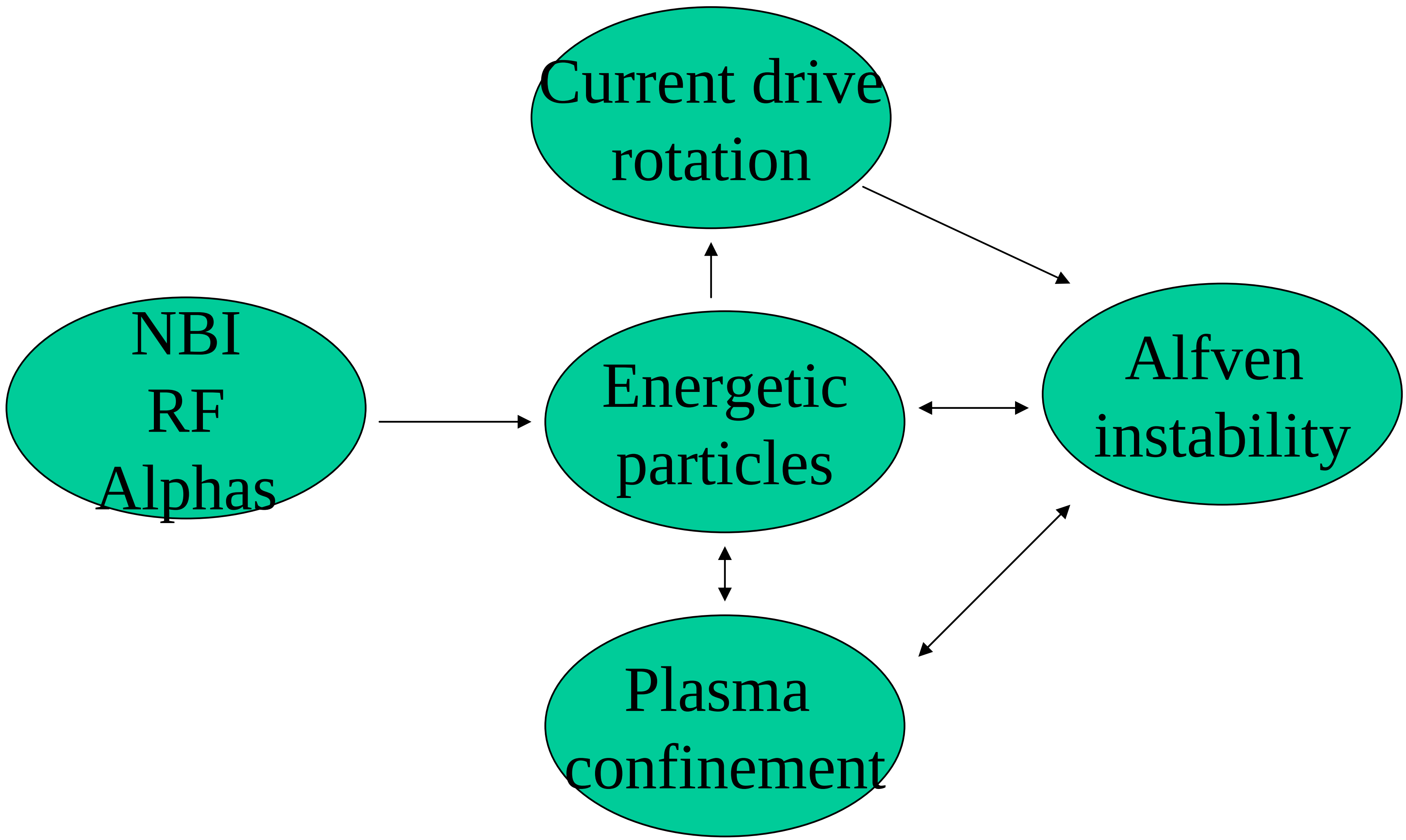


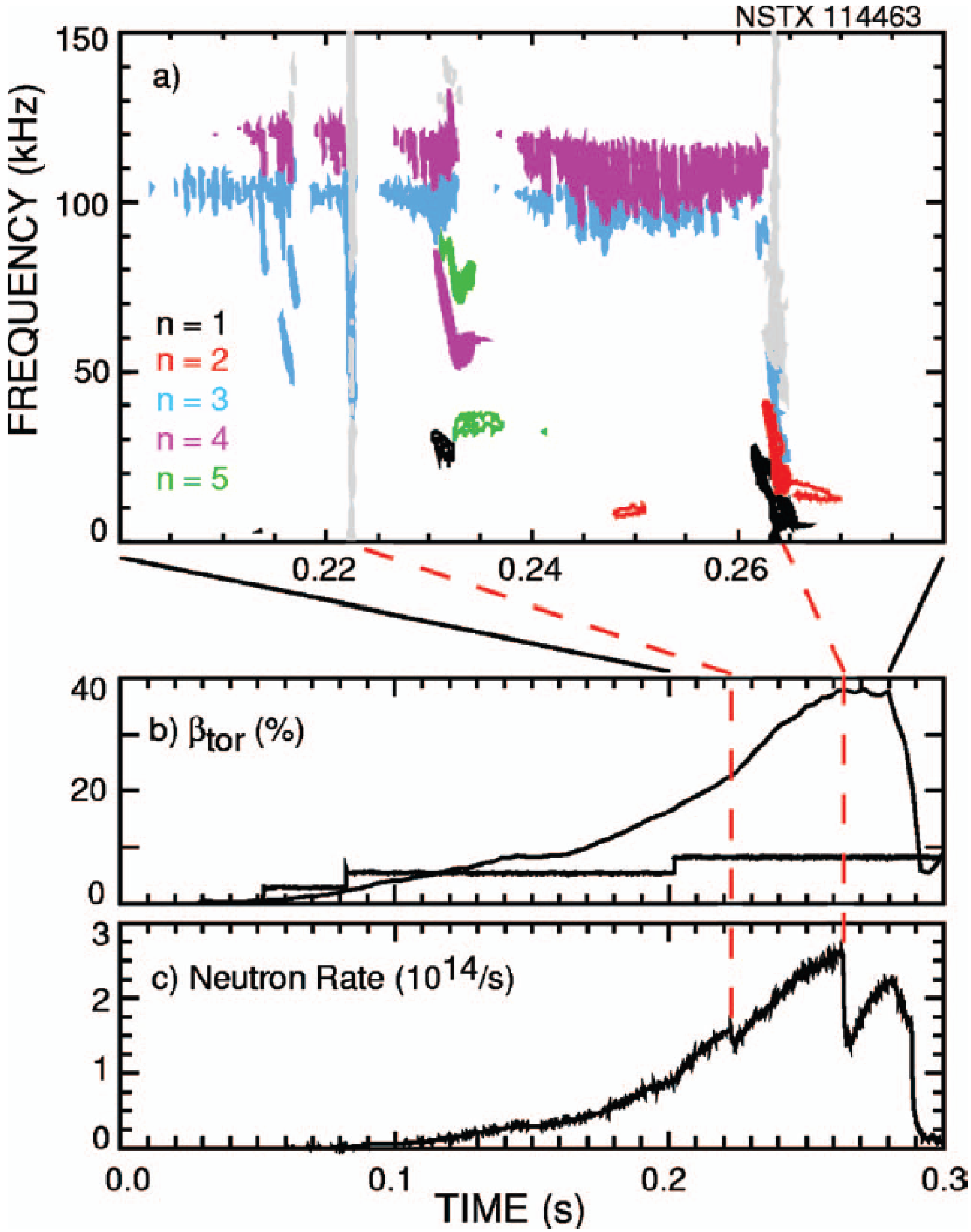
Total pressure

Future Direction for Energetic Particle Physics

- Linear Stability: basic mechanisms well understood, but lack of a comprehensive code which treats dampings and energetic particle drive non-perturbatively
- Nonlinear Physics: single mode saturation well understood, but lack of study for multi-mode dynamics
- Effects of energetic particles on thermal plasmas: needs a lot of work (integrated simulations).

Integration of Energetic Particle Physics





Experimental motivation for integrated simulations

Issues for integrated simulations

- Integration of physics: kinetic MHD
- Integration of different modes
- Integration of different time scale

Integration of physics: kinetic MHD

- Alpha particle stabilization of internal kink mode;
- Energetic particle destabilization;
- FLR effects;
- Ion and electron Landau damping;

Integration of different modes

- TAE
- Fishbone/EPM
- Tearing modes
- KBM

Integration of different time scales

- Shear Alfven time;
- Linear growth time of Alfven eigenmodes;
- Energetic particle slowing down time and velocity diffusion time;
- Plasma confinement time;
- Equilibrium evolution time (q profile).