Energetic Particle Update

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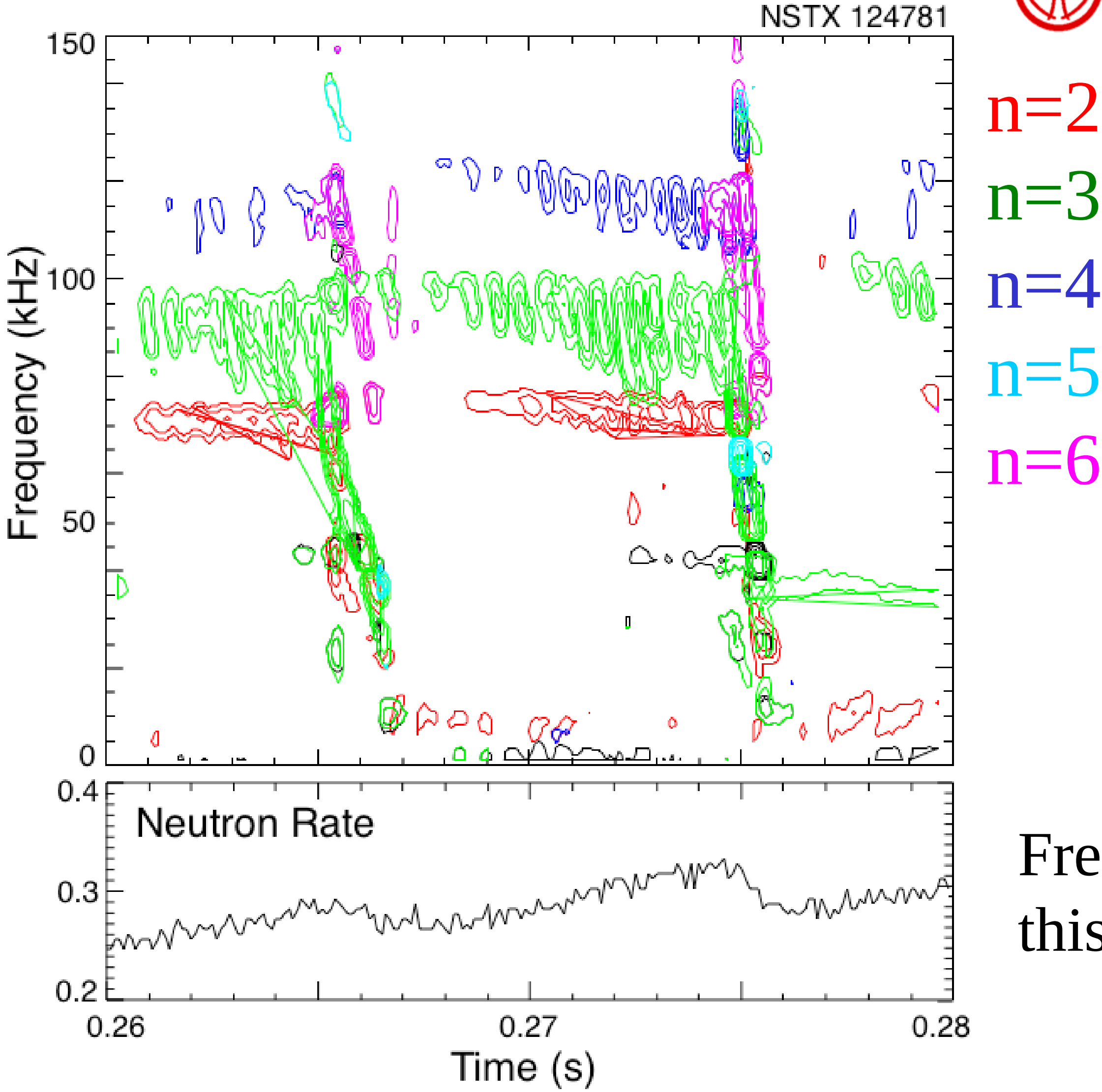
Outline

- Simulations of beam-driven Alfven modes in NSTX
- Simulations of beam-driven GAM in DIII-D

NSTX observes that multi-mode TAE bursts can lead to significant fast-ion redistributions/losses



Fredrickson et al, this meeting.

M3D Particle/MHD Hybrid Model

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

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

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

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

$\mathbf{P}_h$ is calculated using gyrokinetic/drift-kinetic equation (PIC method).

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

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

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

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

δf method (f = f_0 + δf=f_0+g*w)

$$\frac{dw}{dt} = -(\frac{f}{g} - w)\frac{1}{f_0}\frac{df_0}{dt} \quad \text{(B1)}$$

The equilibrium distribution is expressed as a function of the constants of motion:

$$f_0 = f_0(P_\phi, E, \mu) \quad \text{(B2)}$$

where P_ϕ is the toroidal angular momentum, E the energy and μ is the magnetic moment.

Then

$$\frac{df_0}{dt} = \frac{dP_\phi}{dt}\frac{\partial f_0}{\partial P_\phi} + \frac{dE}{dt}\frac{\partial f_0}{\partial E} \quad \text{(B3)}$$

where

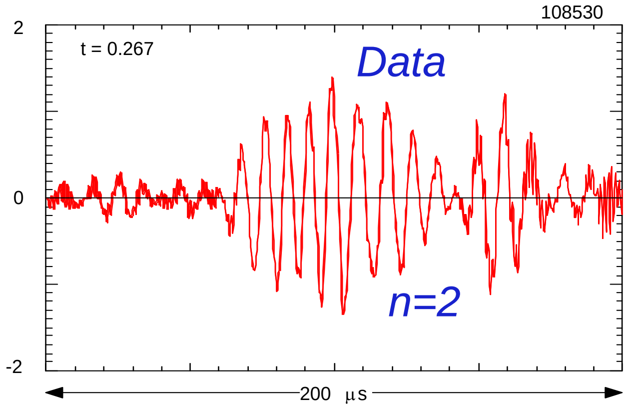
$$\frac{dE}{dt} = e\mathbf{v}_d \cdot < \mathbf{E} > + M\mu\frac{d < \delta B >}{dt} \quad \text{(B4)}$$

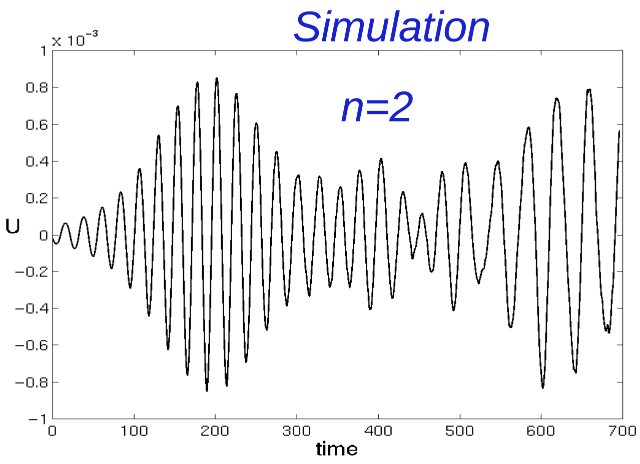
$$\frac{dP_\phi}{dt} = (\frac{d\mathbf{X}}{dt})_1 \cdot \nabla P_\phi + (\frac{dv_\parallel}{dt})_1\frac{\partial P_\phi}{\partial v_\parallel} \quad \text{(B5)}$$

M3D Verification and Validation

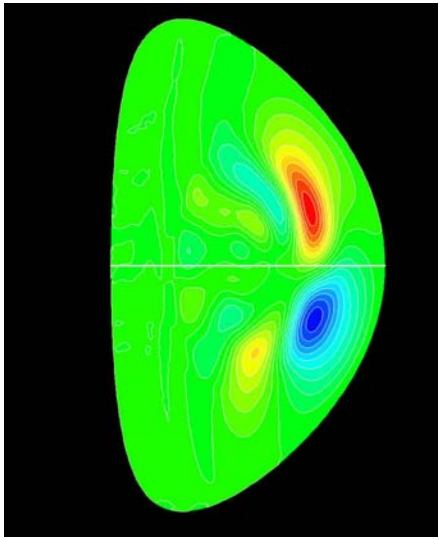
- Good agreement between M3D and NIMROD for CDX-U sawteeth simulations;
- Good agreement between M3D-K and NOVA2 for energetic particle stabilization of internal kink and excitation of fishbone;
- M3D-K results of beam-driven TAEs are consistent with NSTX observations: mode frequency and its chirping, mode saturation time scale.

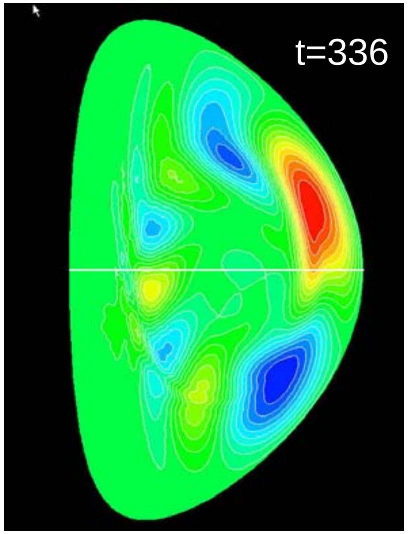
Non-linear single-mode TAE simulations reproduce many features observed in NSTX data

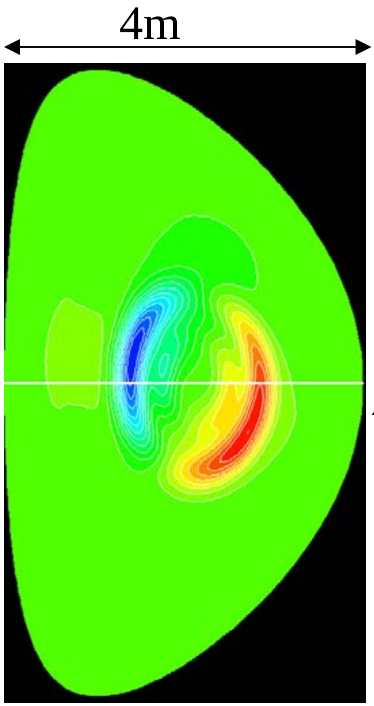




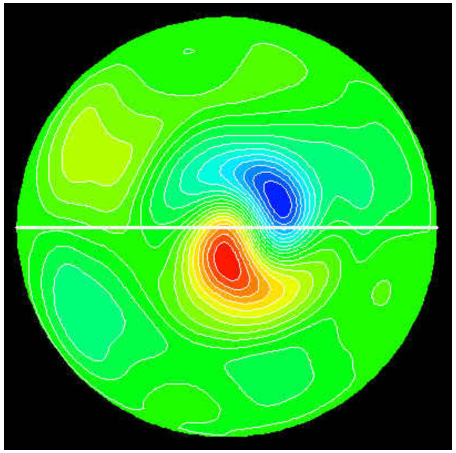
- M3D Nonlinear Hybrid simulations:
  - Mode growth and decay times are approximately 50 - 100 µs
  - Bursting/chirping results from:
    - Non-linear modification of fast-ion distribution
    - Change in mode structure
  - Chirp $\Delta f / f \approx 20\%$ - consistent with experiment







Recent M3D hybrid simulation results:



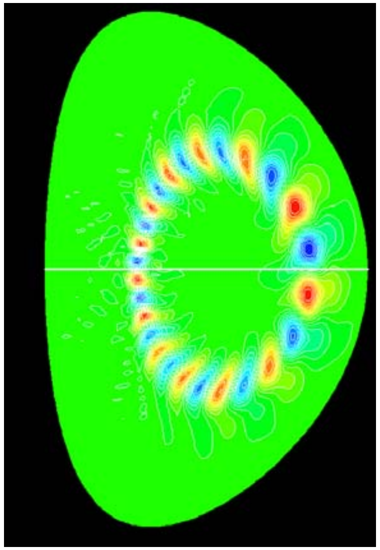
(1) Alpha particle stabilization of n=1 kink in ITER;

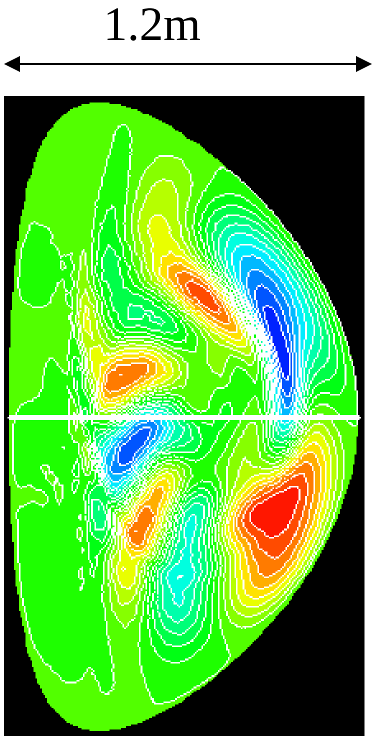
(2) Nonlinear frequency chirping of fishbone;

(3) Beam-driven TAEs in DIII-D;

(4) Beam-driven TAEs in NSTX;

(5) Beam-driven GAM in DIII-D

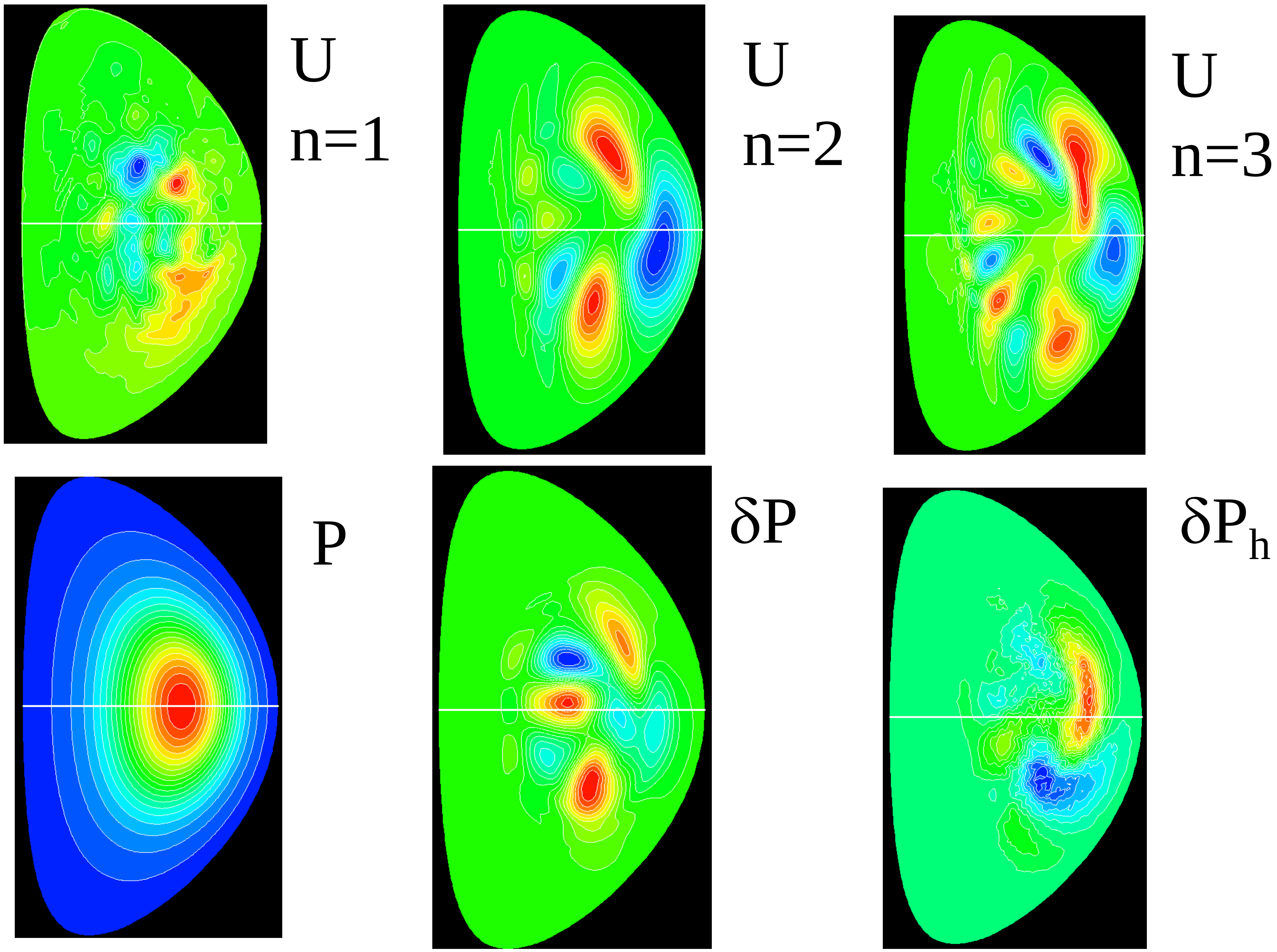




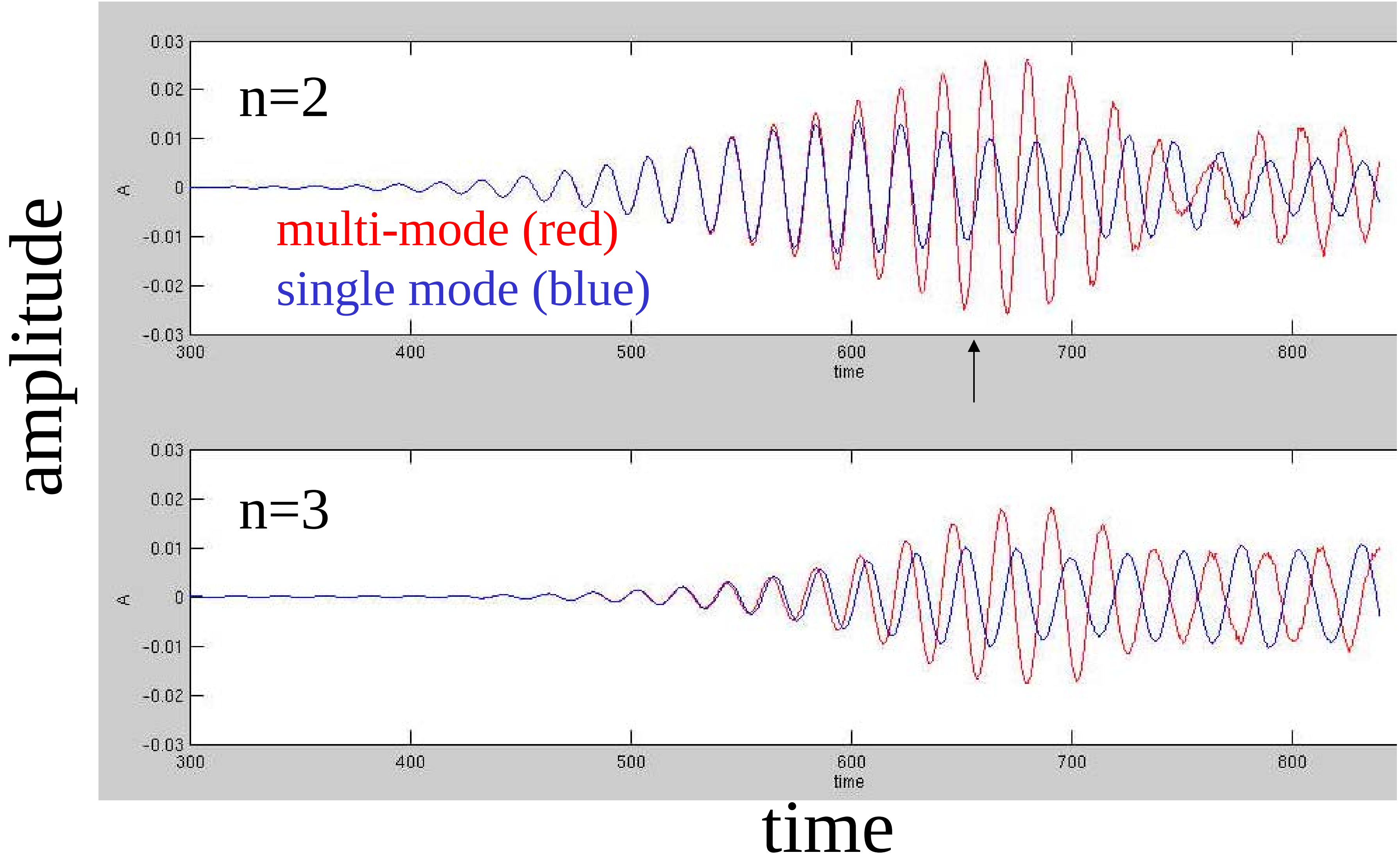
G.Y. Fu, 2004 IAEA Fusion Energy Conference
G.Y. Fu et al., Phys. Plasmas, 2006

Typical NSTX Parameters and Profiles

- R=87cm, a=63cm, B=0.40T,
- q(0)~1.6, q(a)~13, weakly reversed;
  $\beta(0)$~20%, $\beta_{beam} \sim \beta_{thermal}$;
- $v_{beam}/v_{Alfven} \sim 2$, $\rho_{beam}/a \sim 0.2$


U
n=1
U
n=2
U
n=3
P
δP
δP
h

Multi-mode simulations show strong mode-mode interaction.

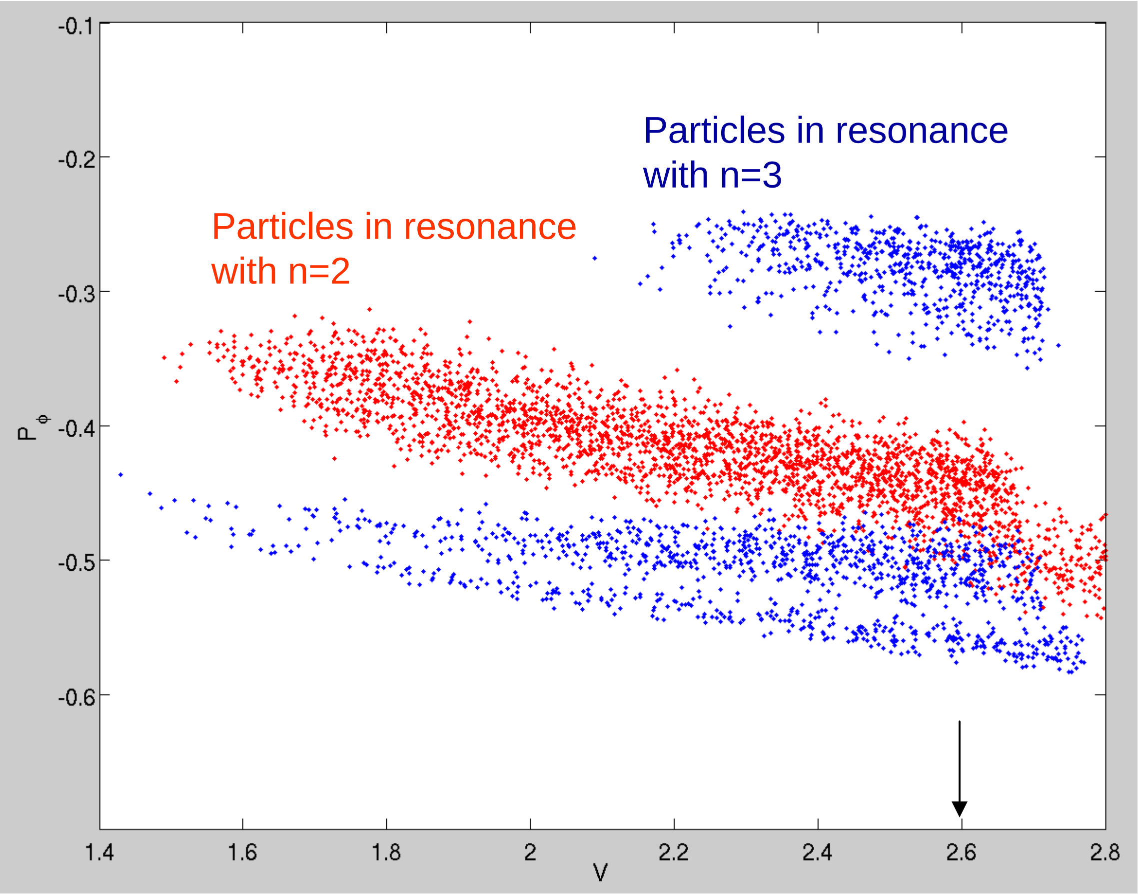


Strong interaction between different modes is due to wave-particle resonance overlap

Edge→

P_φ

Axis→



$\Lambda=\mu B/E=0.6$

V

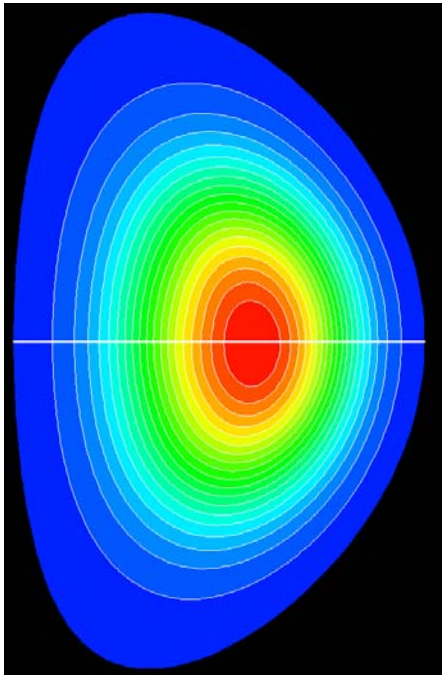
Injection speed

Energetic Particle-driven GAM

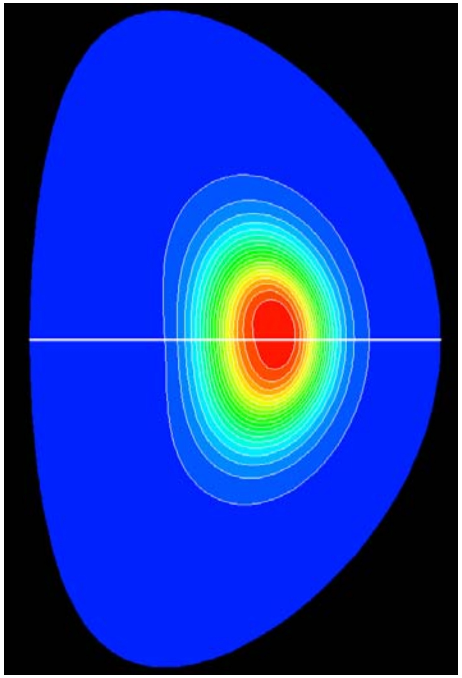
- Motivated by n=0 mode in JET and Berk et al's explanation of energetic particle-driven GAM;
- More recent finding of n=0 mode driven by beam ions in DIII-D and JET;
- M3D simulations show GAM-like mode can be excited by energetic beam ions. This is first direct numerical demonstration of energetic particle destabilization of GAM.

Excitation of GAM by beam ions in DIII-D

P

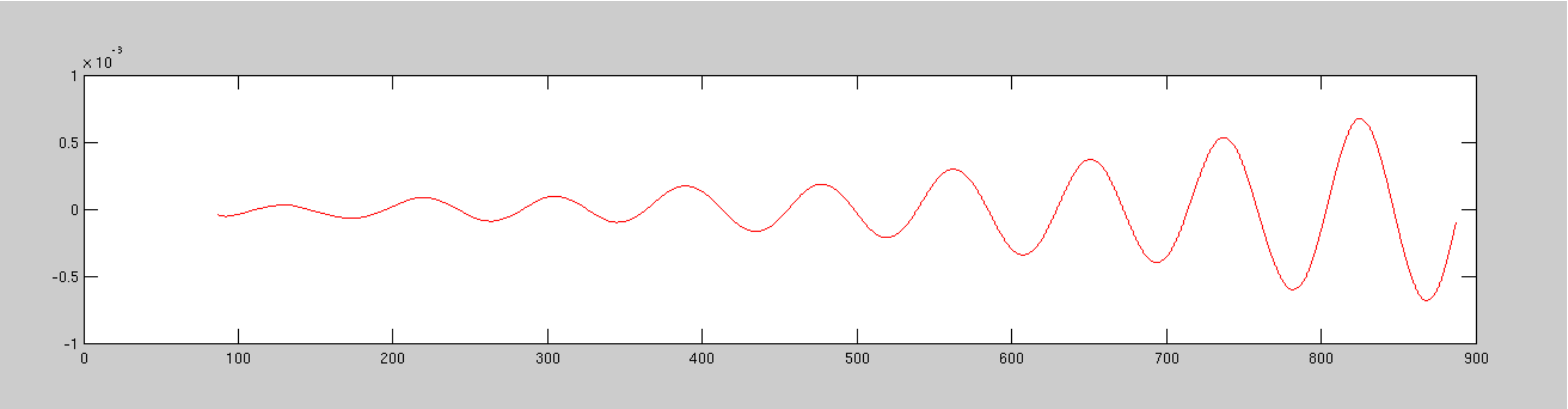


Φ



Evolution of electric potential

Φ



t (Alfven time)

$\omega \quad = 0.074$

$\omega_{GAM} = 0.088$ (at axis)

M3D Results of n=0 mode

- The mode is driven by anisotropic distribution of beam ions (velocity space);
- The mode is mostly n=0/m=0;
- The mode frequency is slightly below the local GAM frequency at the magnetic axis indicating EPM-like mode.

Summary

- Strong nonlinear coupling between multiple modes due to resonance overlap for beam-driven TAE modes in NSTX;
- First demonstration of energetic particle-driven GAM in tokamaks.