Recent Results from Kinetic-MHD Hybrid Simulations of Energetic Particle-driven Modes in NSTX

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**SicDAC Center for Nonlinear Simulation of Energetic Particles in Burning Plasmas (CSEP)*

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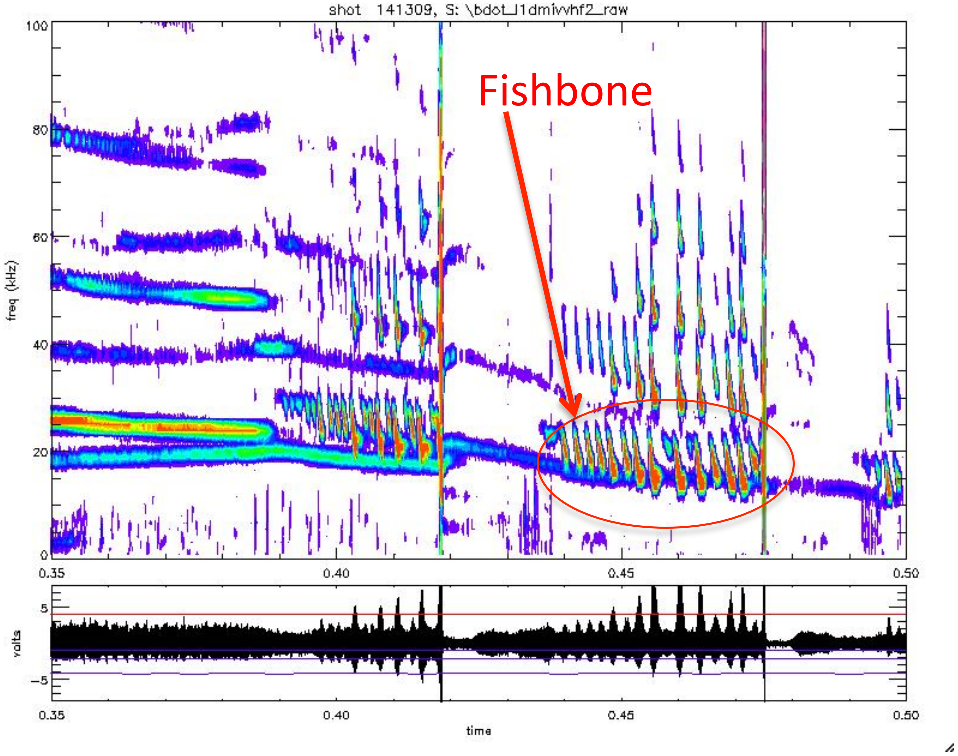
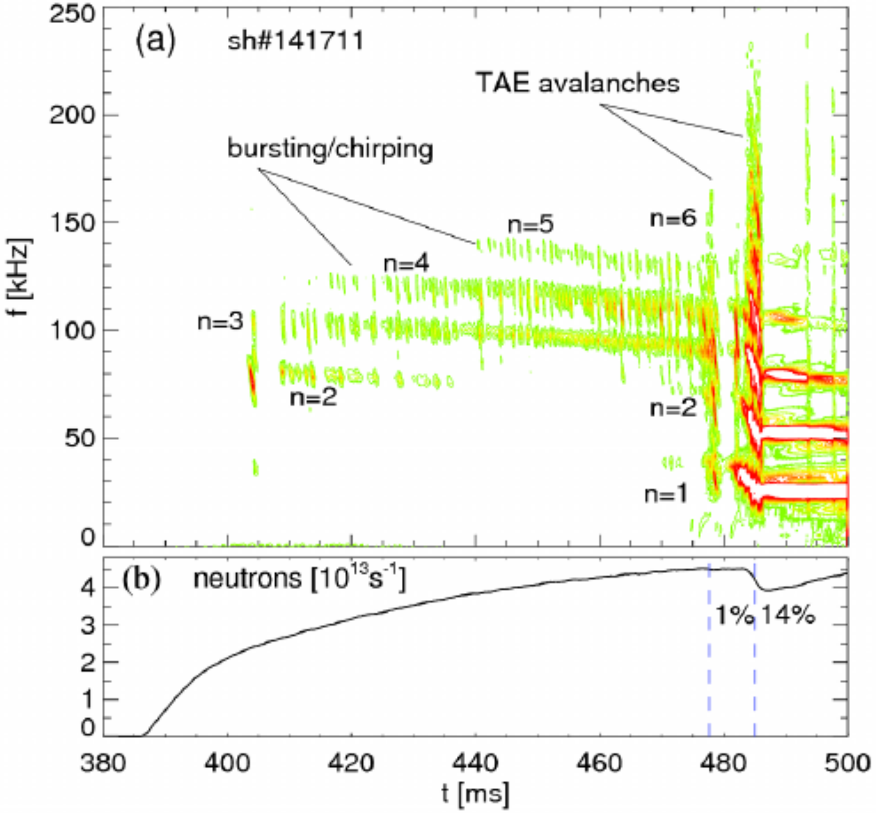
Outline

1. Introduction
2. Non-resonant kink and fishbone in NSTX
3. Beam-driven TAEs in NSTX
4. Conclusions

Beam-driven fishbones and Alfven modes are routinely observed in NSTX.





Recent Work on EP-driven Modes and EP transport in NSTX

- “Three-wave interactions between fast-ion driven modes in the National Spherical Torus Experiment”, Crocker, PoP 2009;
- “Experimental studies on fast-ion transport by Alfvén wave avalanches on the National Spherical Torus Experimenta”, Podesta, PoP 2009;
- “Modeling fast-ion transport during toroidal Alfvén eigenmode avalanches in National Spherical Torus Experiment”, Fredrickson, PoP 2009;
- “On the anomalous fast ion energy diffusion in toroidal plasmas due to cavity modes”, Gorelenkov, PPCF 2010
- “Non-linear dynamics of toroidicity-induced Alfvén eigenmodes on the National Spherical Torus Experiment”, Podesta, Nucl. Fusion, 2011;
- “Observation of global Alfvén eigenmode avalanche events on the National Spherical Torus Experiment”, Fredrickson, Nucl. Fusion, 2012;
- “Study of chirping toroidicity-induced Alfvén eigenmodes in the National Spherical Torus Experiment”, Podesta, Nucl. Fusion, 2012;
- “Investigation of a transient energetic charge exchange flux enhancement….”, Medley, Nucl. Fusion 2012
- “Fast-ion energy loss during TAE avalanches in the National Spherical Torus Experiment”, Fredrickson, Nucl. Fusion, 2013;
- “Stochastic orbit loss of neutral beam ions….”, Darrow, Nucl. Fusion, 2013;
- “Linear stability and nonlinear dynamics of the fishbone mode in spherical tokamaks”, Wang, PoP 2013
- “Parametric dependence of fast-ion transport events on the National Spherical Torus Experiment”, Fredrickson, Nucl. Fusion 2014;
- “A reduced fast ion transport model for the tokamak transport code TRANSP”, Podeta, PPCF 2014;
- Beam-driven GAE & CAE, Belova, PRL 2015
- Beam-driven TAEs, Liu, PoP 2015

Introduction: motivation

- Energetic particle (EP)-driven instabilities can induce significant alpha particle redistribution and losses to the first wall of fusion reactors;
- Energetic particle can interact with thermal plasma strongly: affect equilibrium, stability and transport. EP physics is a key element for understanding and controlling burning plasmas.
- M3D-K simulations of beam-driven modes in NSTX are carried out for code validation and physics understanding

M3D-K is a global nonlinear kinetic/MHD hybrid simulation code for toroidal plasmas

G.Y. Fu, J. Breslau, L. Sugiyama, H. Strauss, W. Park, F. Wang et al.

$$\rho \frac{d\mathrm{v}}{dt} = -\nabla P_{th} - \nabla \cdot P_h + J \times B \qquad \frac{dP_{th}}{dt} = -\gamma P_{th} \nabla \cdot \mathrm{v}$$

$$J = \nabla \times B \qquad \frac{\partial B}{\partial t} = -\nabla \times E \qquad E + \mathrm{v} \times B = \eta J$$

*The energetic particle stress tensor, P_h, is calculated using drift kinetic or gyrokinetic equation via PIC.
*Mode structures are evolved self-consistently including non-perturbative effects of energetic particles;
*Include plasma rotation

G.Y. Fu et al, PHYSICS OF PLASMAS 13, 052517 (2006)

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Linear Stability and Nonlinear Dynamics of Fishbone in NSTX

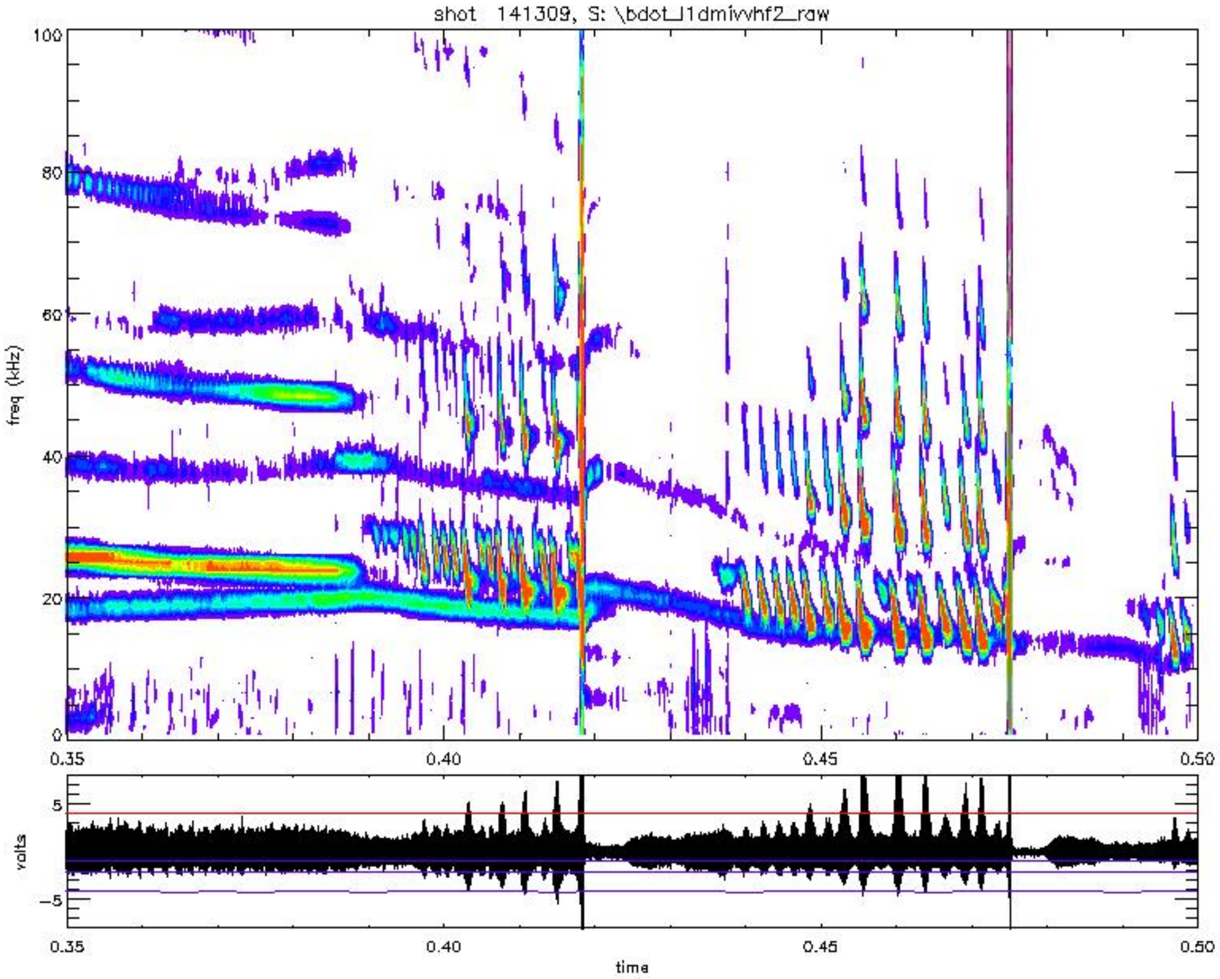
F. Wang, G.Y. Fu, J. Breslau, J.Y. Liu, Phys. Plasmas 2013,

- We consider NSTX plasmas with a weakly reversed q profile and q_min close but above unity.
- For such q profile, fishbone and non-resonant kink mode (NRK) have been observed in NSTX and MAST.
- M3D-K code is used to simulate beam ion effects on n=1 mode: stabilization of NRK, excitation of fishbone and nonlinear dynamics
- New Results:

  Effects of toroidal rotation on linear stability;

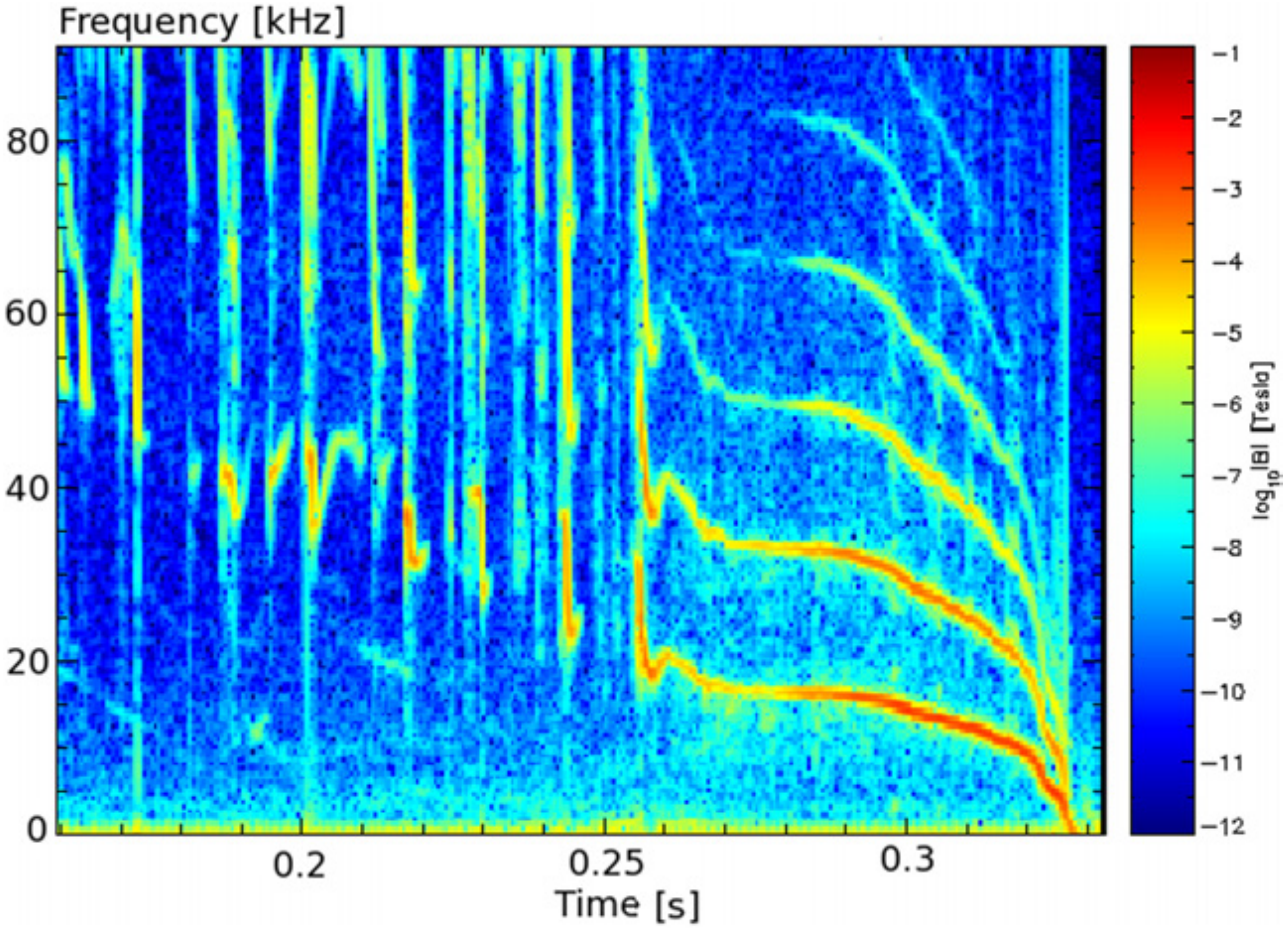
  Nonlinear phase space dynamics → frequency chirping.

Beam-driven fishbones are observed in NSTX

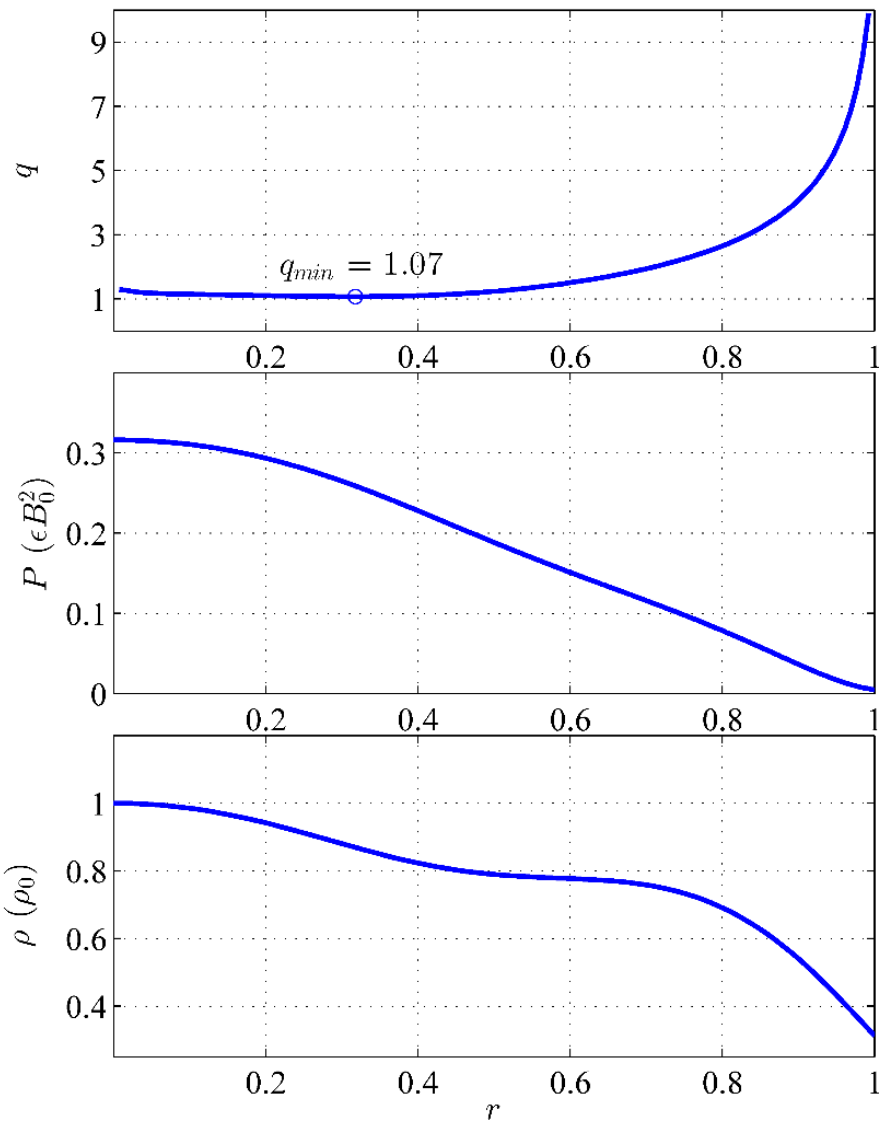


Fishbone and NRK (LLM) were observed in STs and tokamaks

I.T. Chapman et al., Nucl. Fusion 50, 045007 (2010)



Equilibrium profile and parameters



NSTX #124379 at t=0.635s

- ➢NSTX parameters

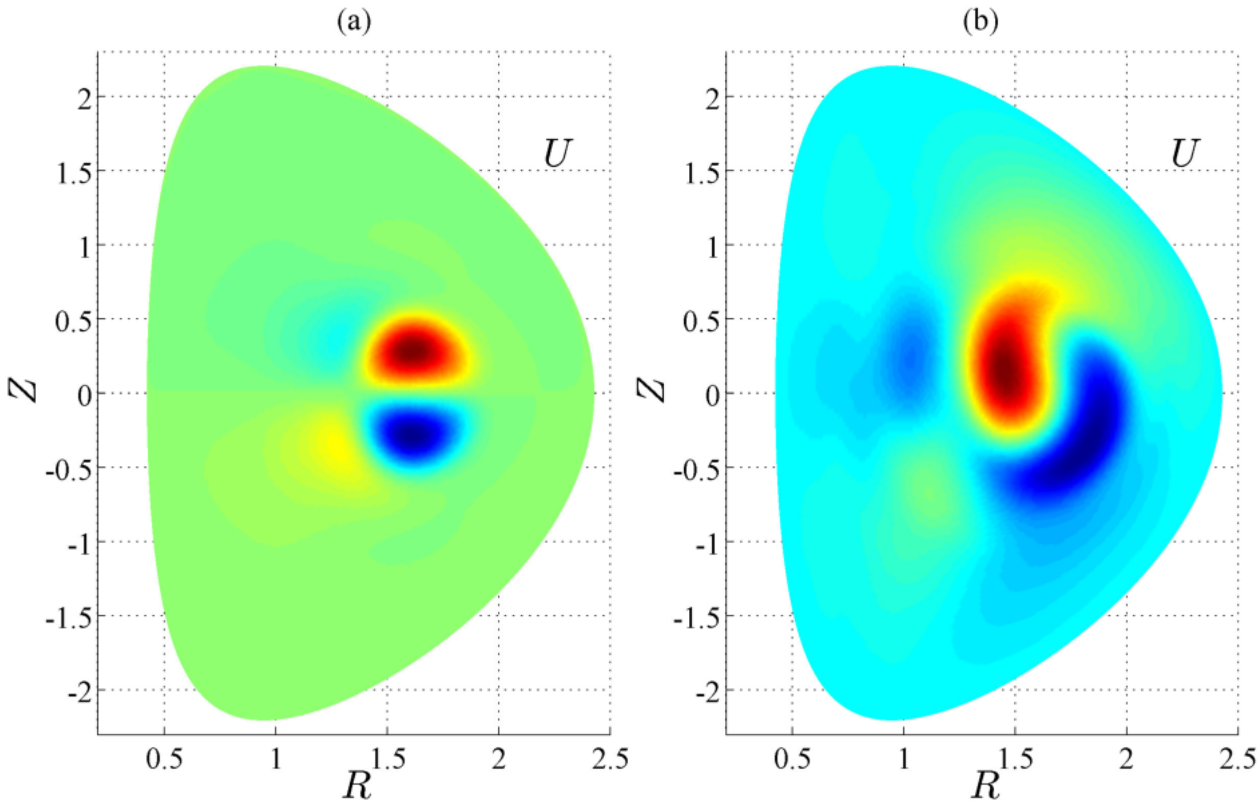
B_0 =0.44T, R=0.86m, a=0.60m

$n_e(0)$=9.3x 10^{13} cm^{-3}

$\beta_{tot}(0)$=30%

Analytic fast ion distribution

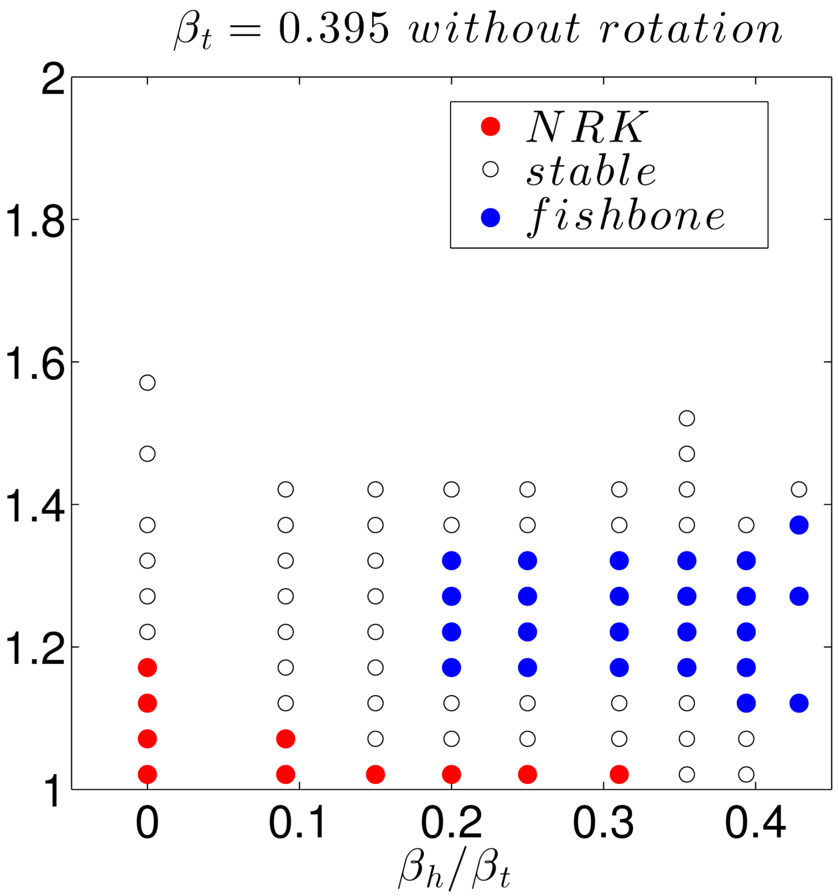
The fishbone mode structure shows twisting feature

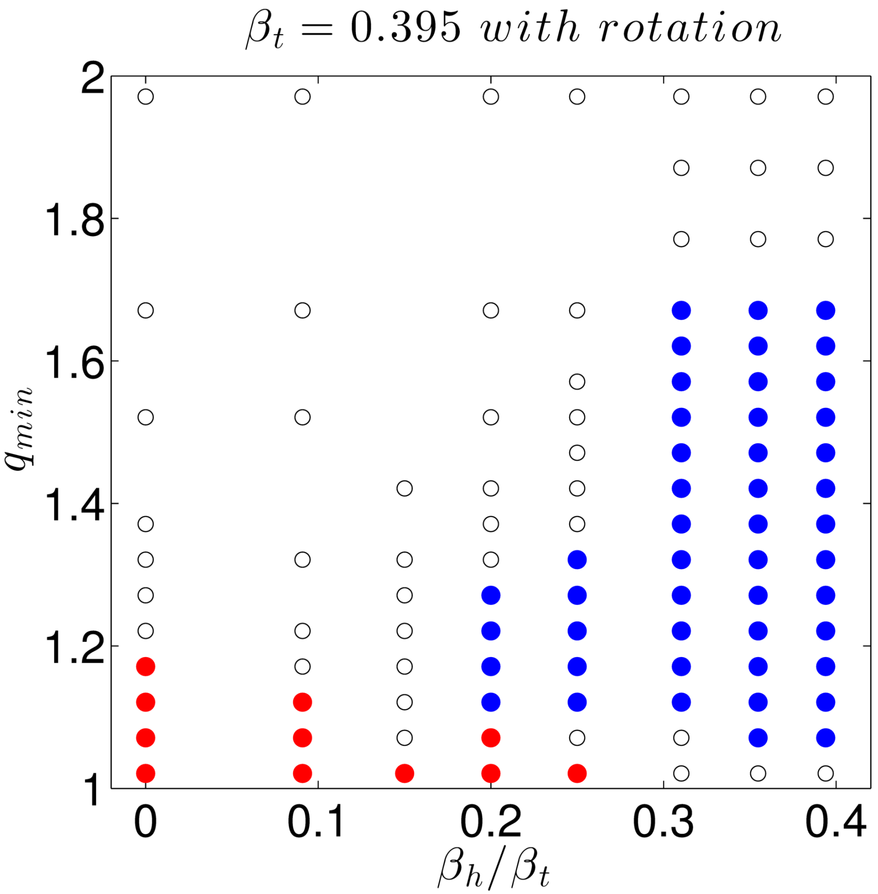


NRK

fishbone

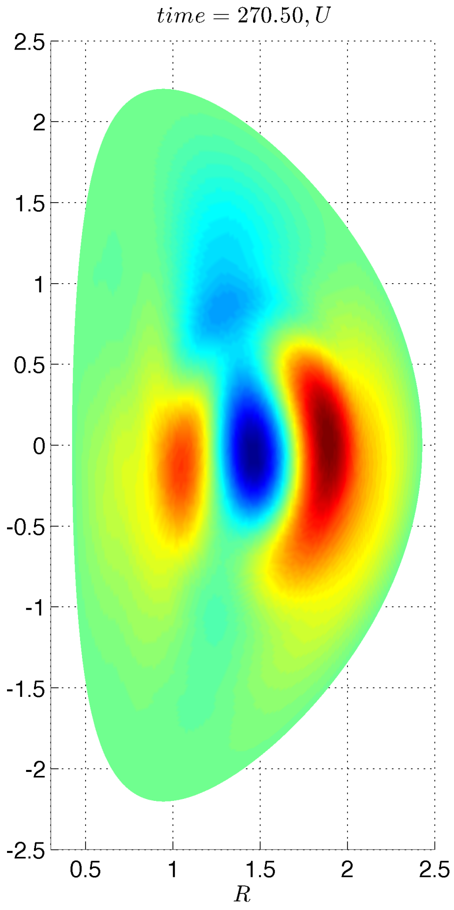
Plasma rotation destabilizes fishbone at higher q_{min}



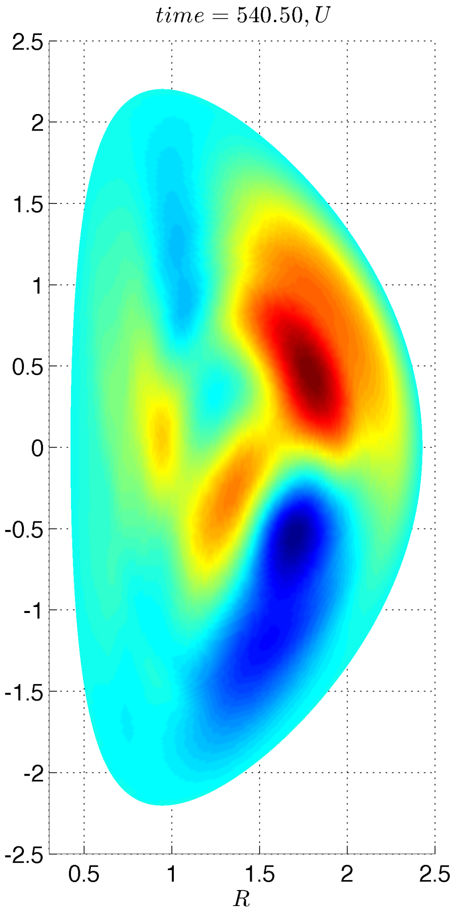


Fishbone has ballooning structure at higher q_{min}

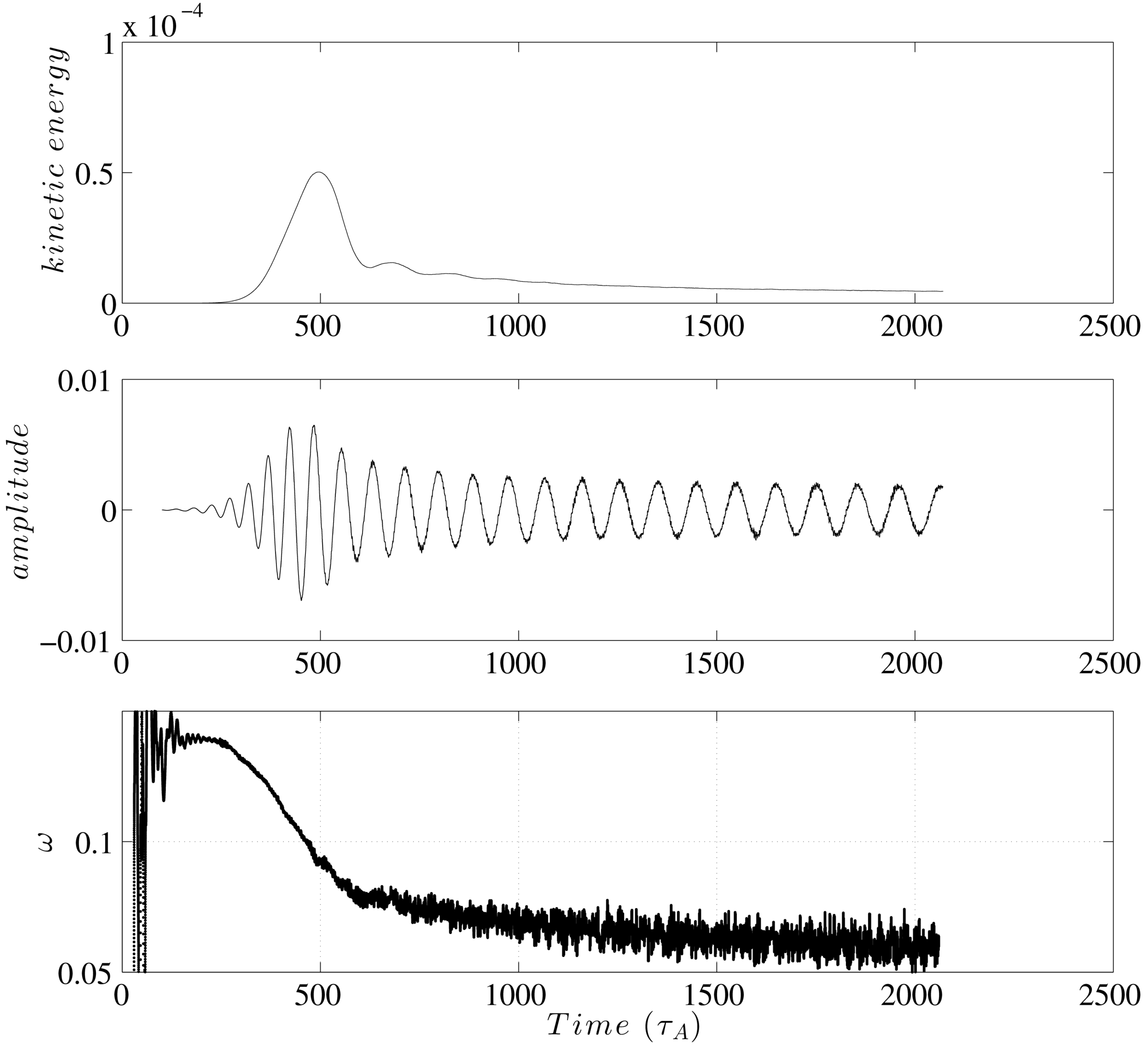
q_{min}=1.171

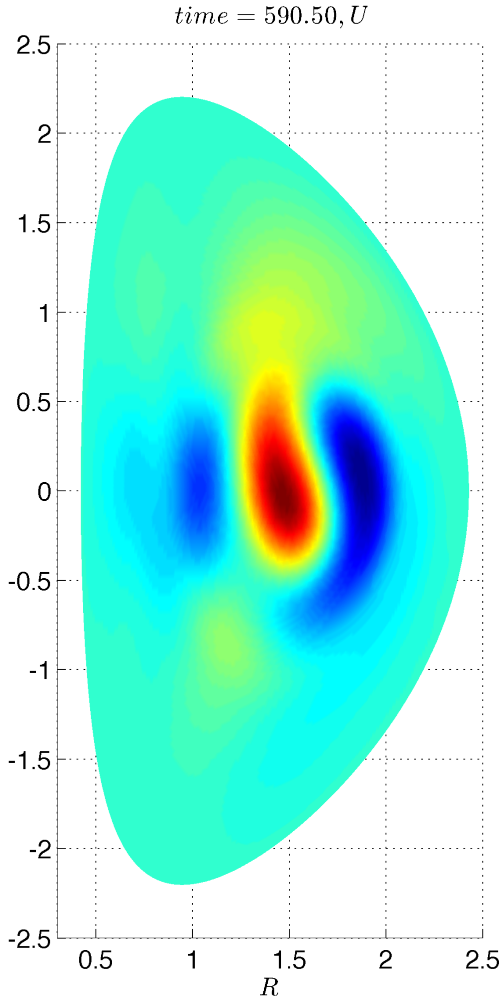


q_{min}=1.621

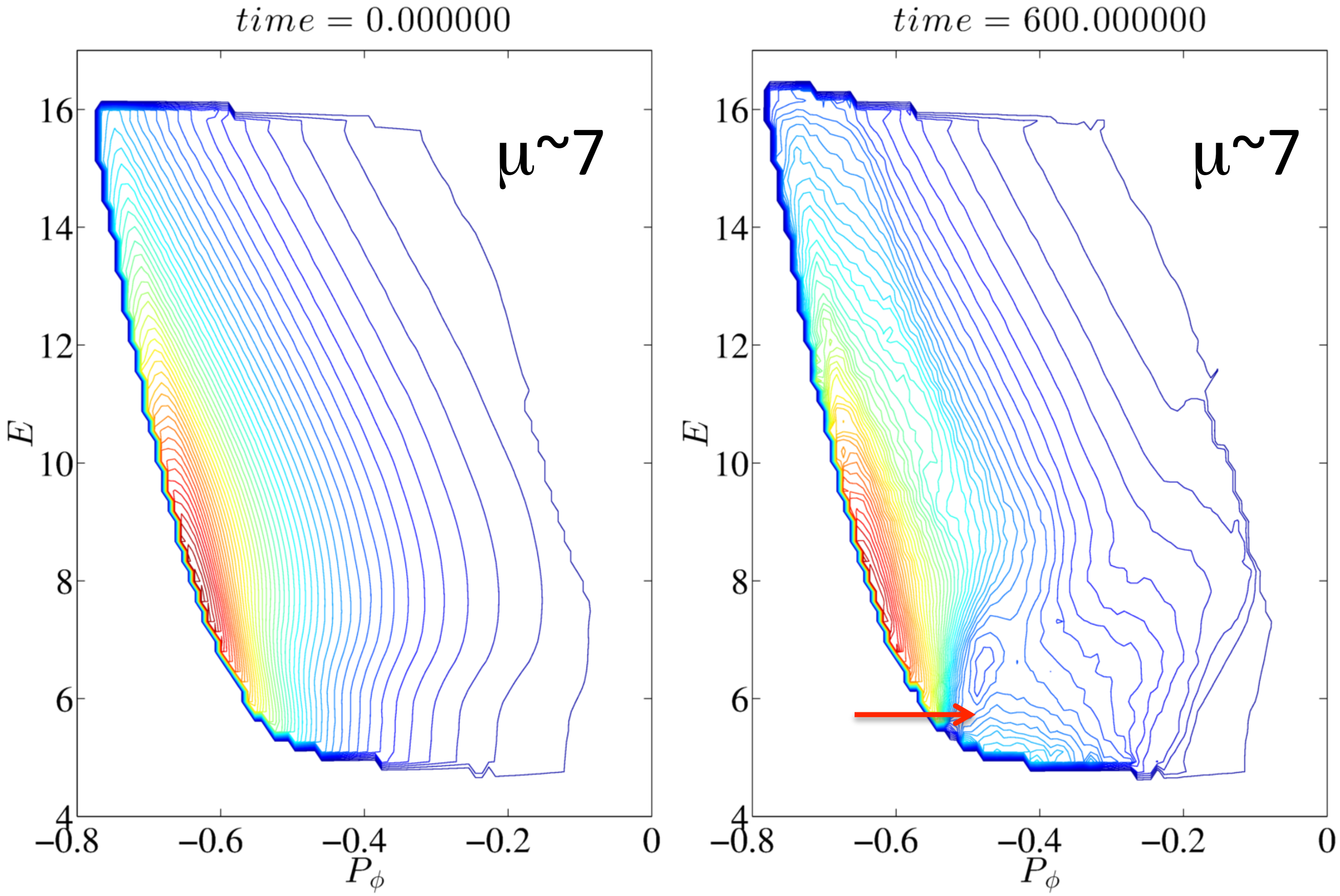


Fishbone nonlinear evolution with plasma rotation: saturation and strong frequency chirping



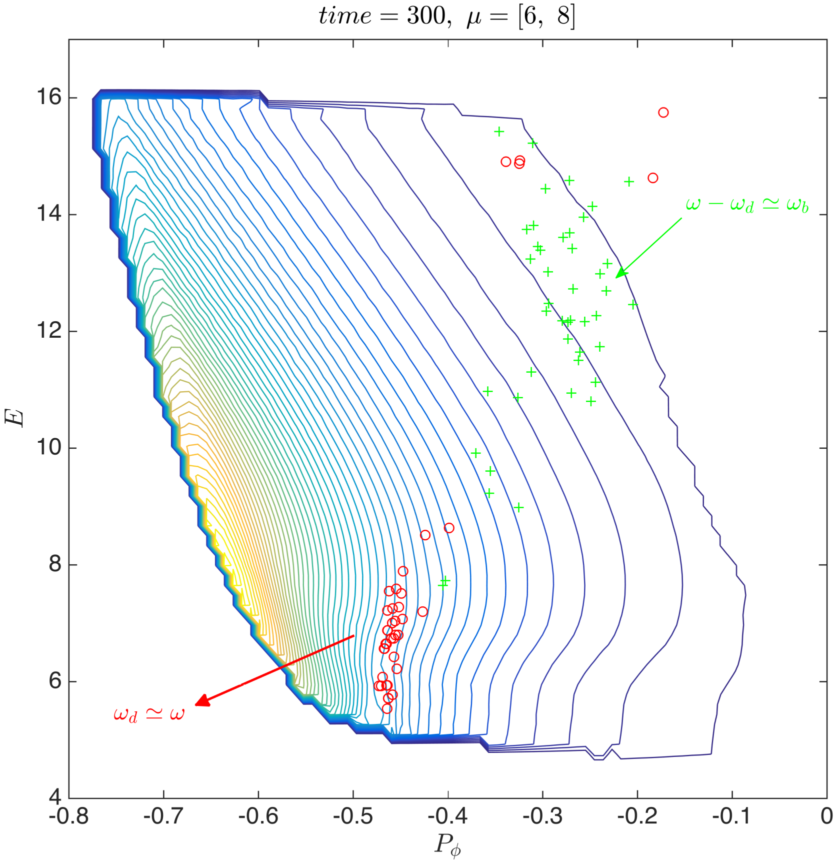


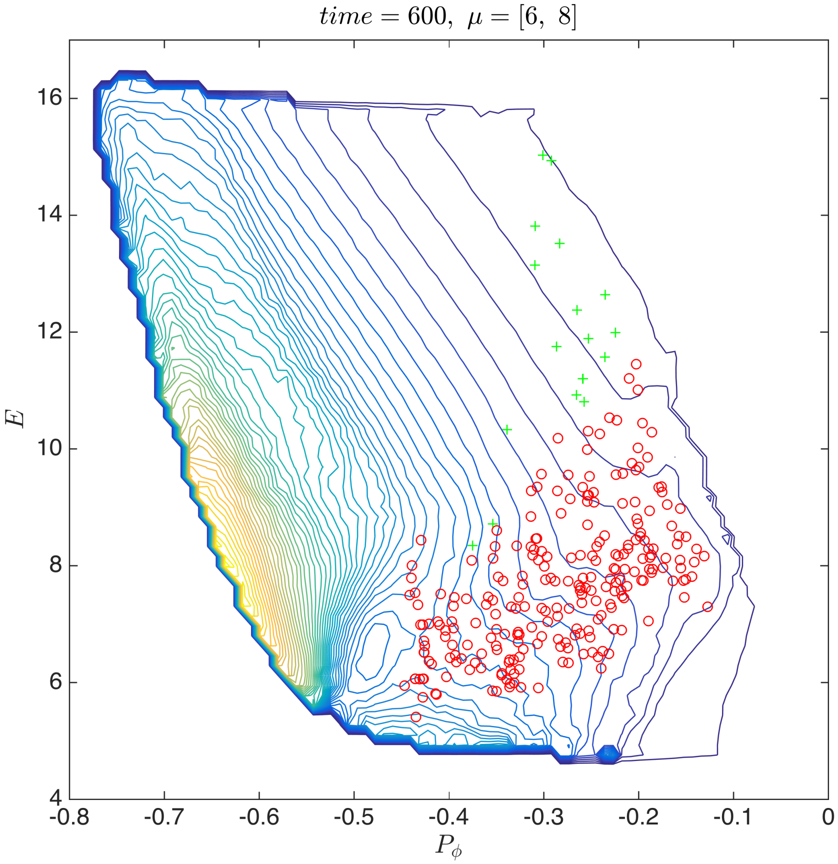
Beam ion distribution (2D) is flattened for lower energy after mode saturation



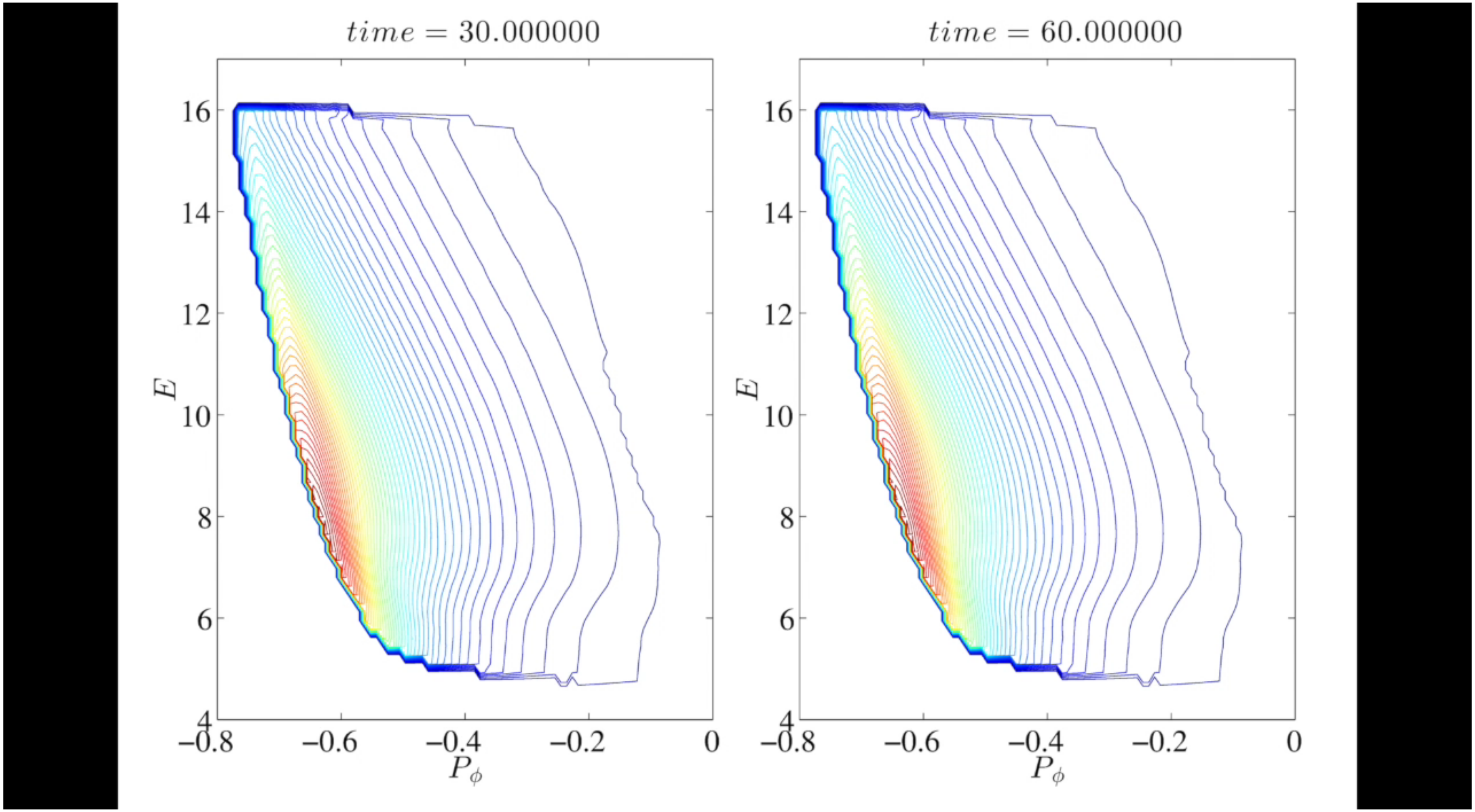
Comparison of beam ion distribution between t=0 and t=600

Precessional drift resonance ($\omega=\omega_d$) is the dominating resonance

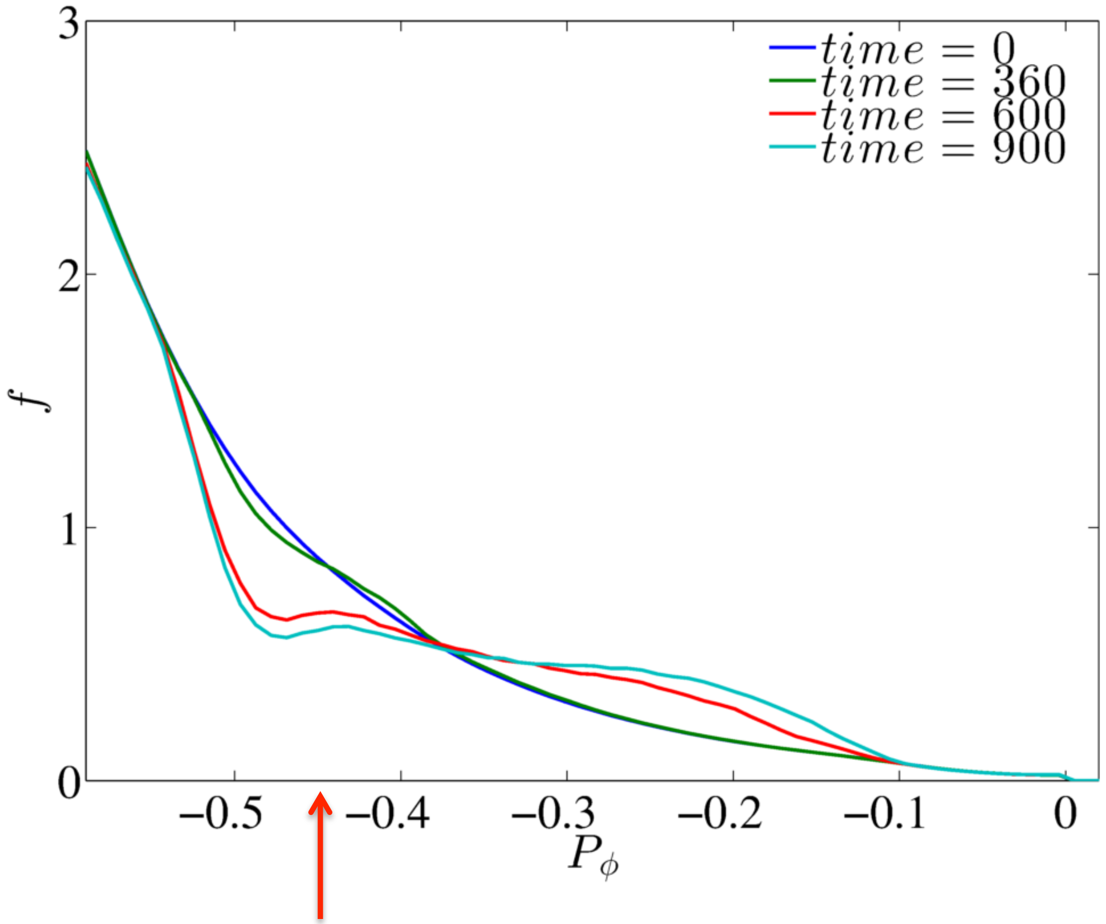




Evolution of beam ion distribution (2D)



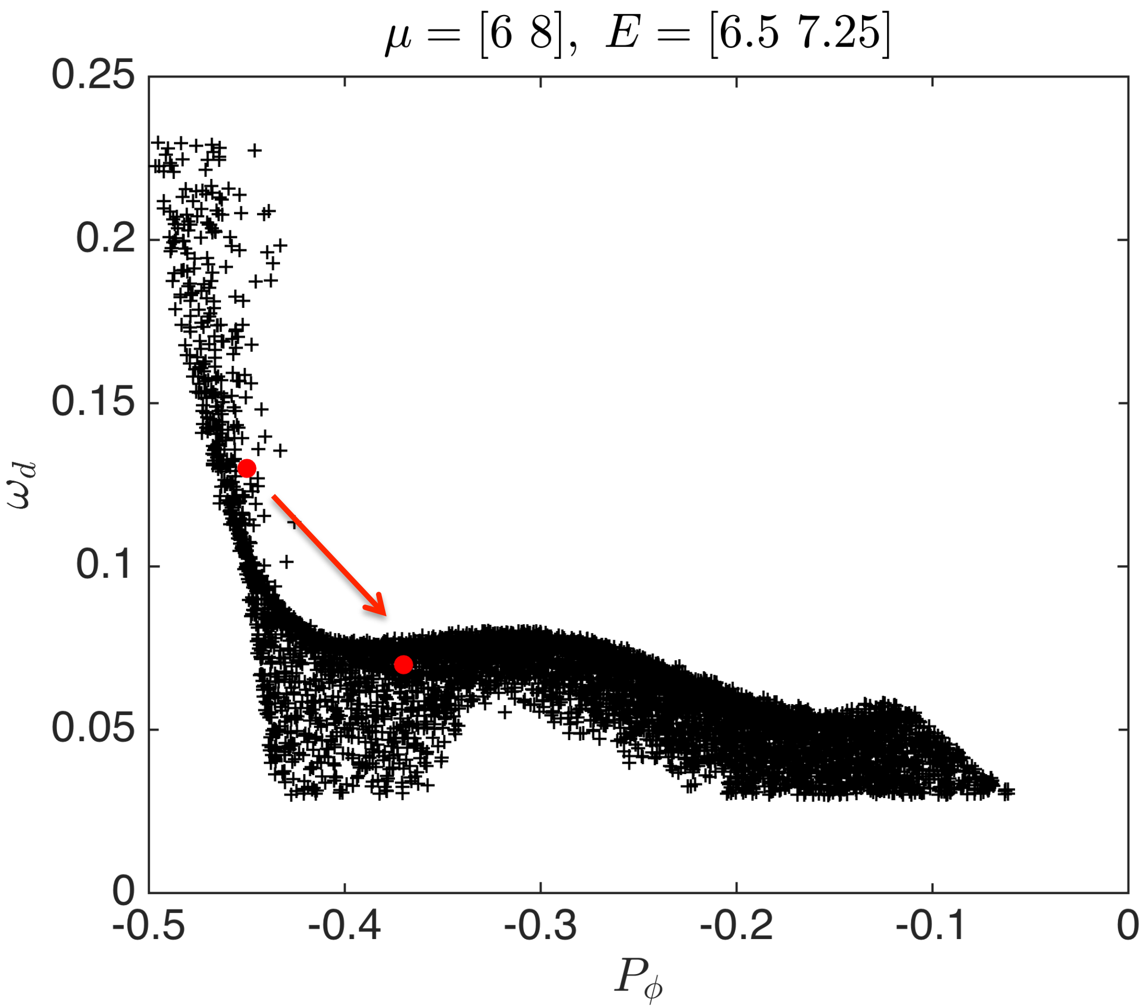
Evolution of beam distribution (1D)



E~[5.1 8.5],
μ~[6, 8]

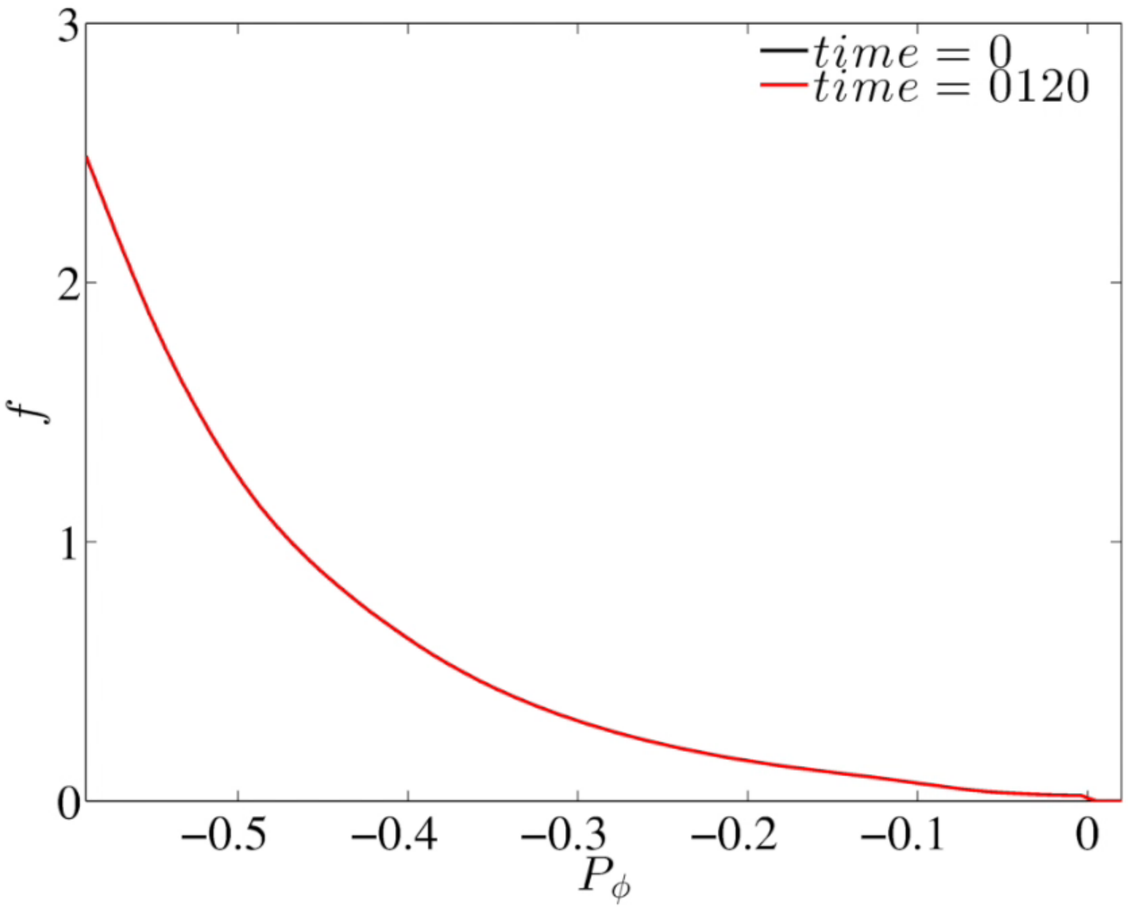
Linearly, resonant location P_ϕ=-0.46
Nonlinearly, resonant location move from -0.46 to -0.37

Precession drift frequency decreases as particles move out



Particle precession drift frequency as a function of P_ϕ

Movie: evolution of beam ion distribution (1D)



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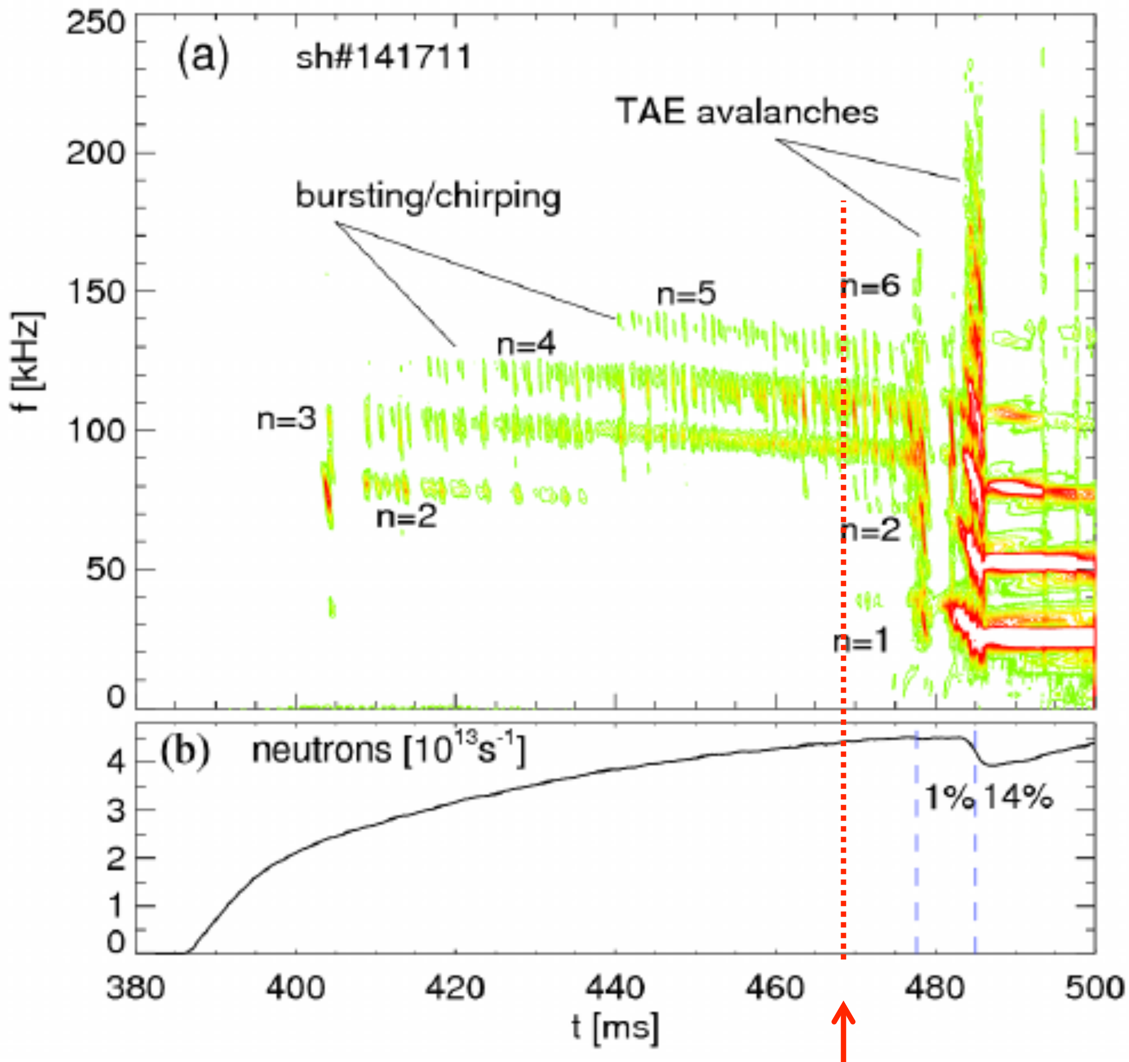
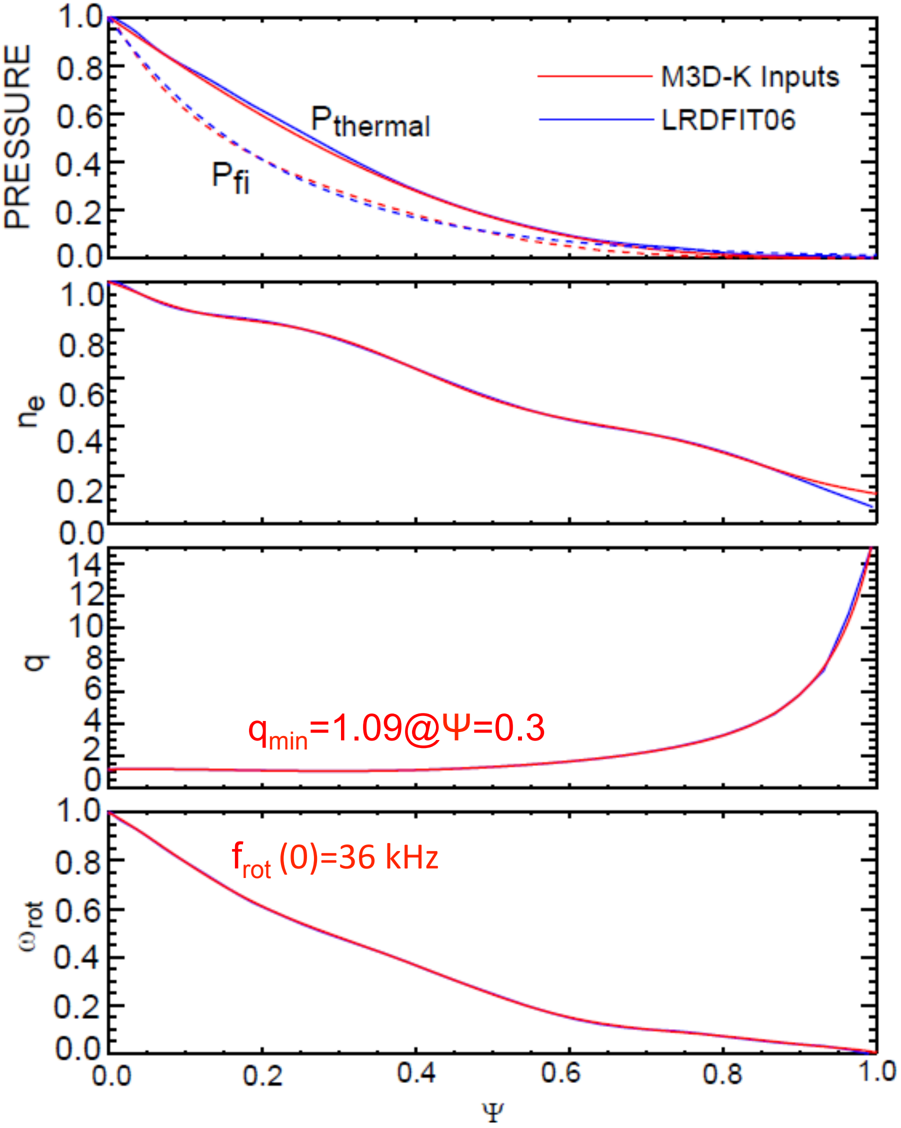
Beam-driven TAEs are routinely observed in NSTX.



t=470ms

Experimental Plasma Parameters and Profiles are Used for TAE Simulation



➢NSTX parameters (B_0 =0.55T, R=0.85m, a=0.67m) and equilibrium profiles at 470 ms of shot 141711

- $n_e(0)$=4.4x 10^{13} cm^{-3}
- $T_e(0)$=1.4 keV
- $T_i(0)$=1.3 keV

➢ Self-consistent equilibrium with plasma rotation and fast ion pressure

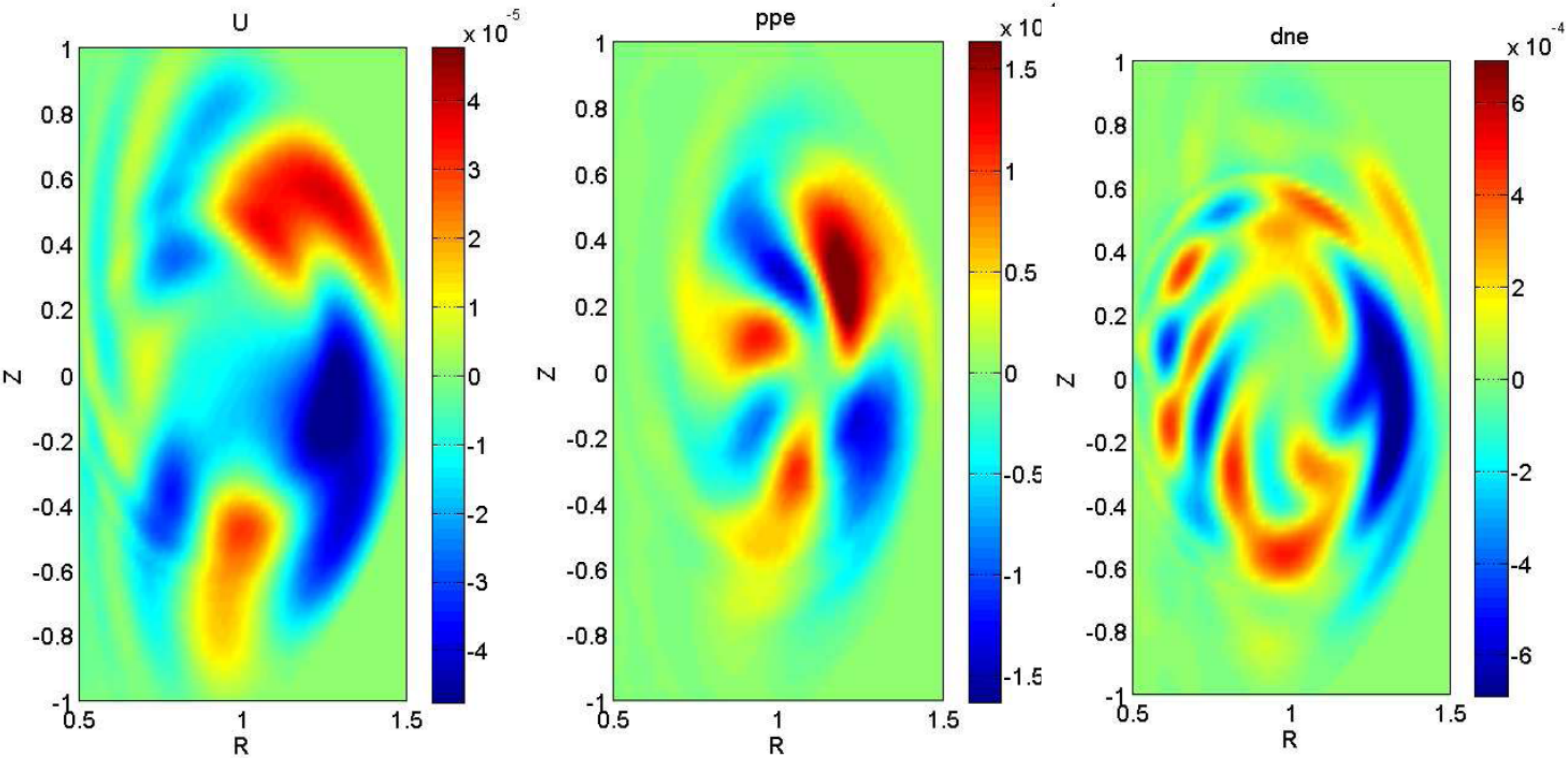
- $\beta_{tot}(0)$=18.4%, $\beta_{fi}(0)$=6.5%
- analytic or numerical fast ion distribution

$$f = \frac{cH(v_0 - v)}{v^3 + v_c^3} \exp(-\psi / \Delta\psi) \exp[-(\Lambda - \Lambda_0)^2 / \Delta\Lambda^2], \Lambda = \frac{\mu B}{E}$$

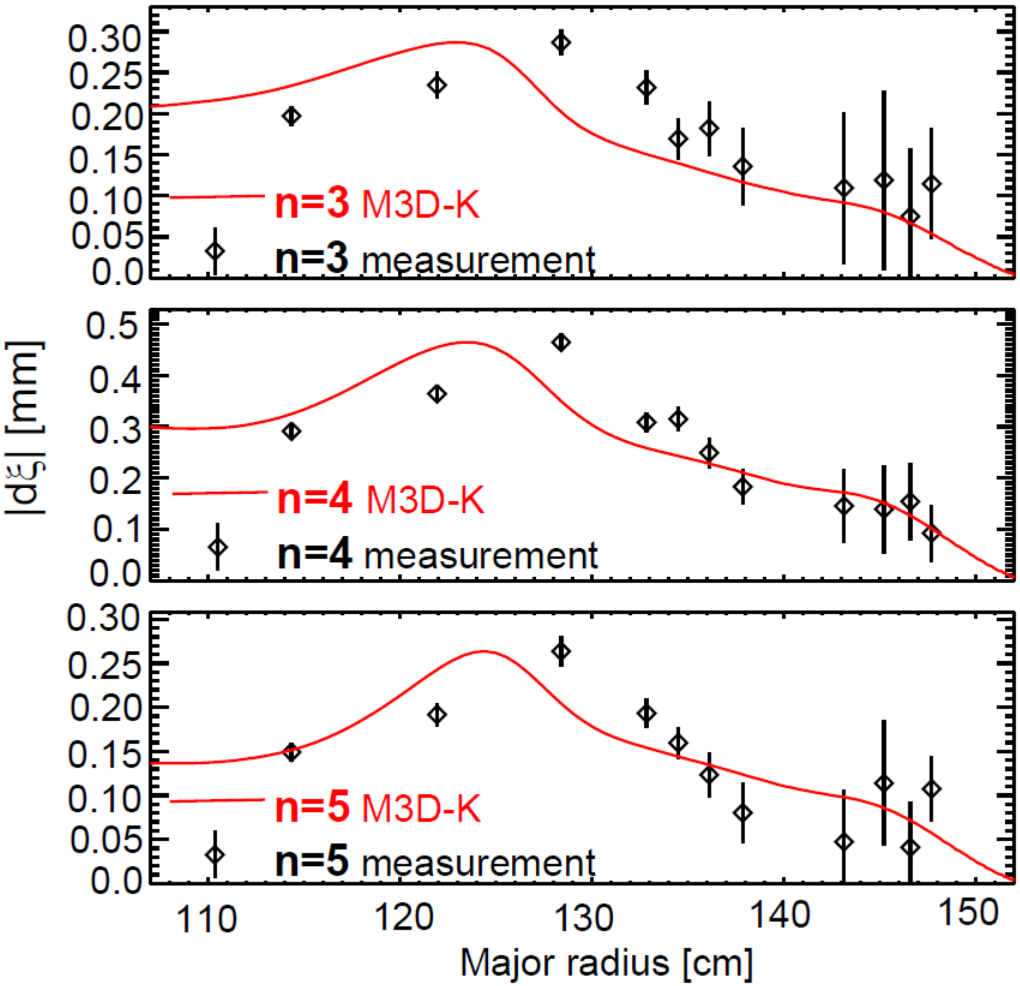
v_{fi} / v_{alfven}=2.5, P_{NBI}= 2MW

n=3 Simulation Exhibits TAE-like Global Feature

U $P_{//}$ δn



Mode Structure and Mode Frequency of Simulated n=3,4,5 TAE are in reasonable agreement with Experimental Measurements



Black: NSTX reflectometer measurements

Red: M3D-K synthetic reflectometer response

D. Liu et al, PoP 2015

	n=3	**n=4**	**n=5**
f_{exp} (kHz)	**100**	**120**	**140**
$f_{M3D\text{-}K}$ (kHz)	106	130	149

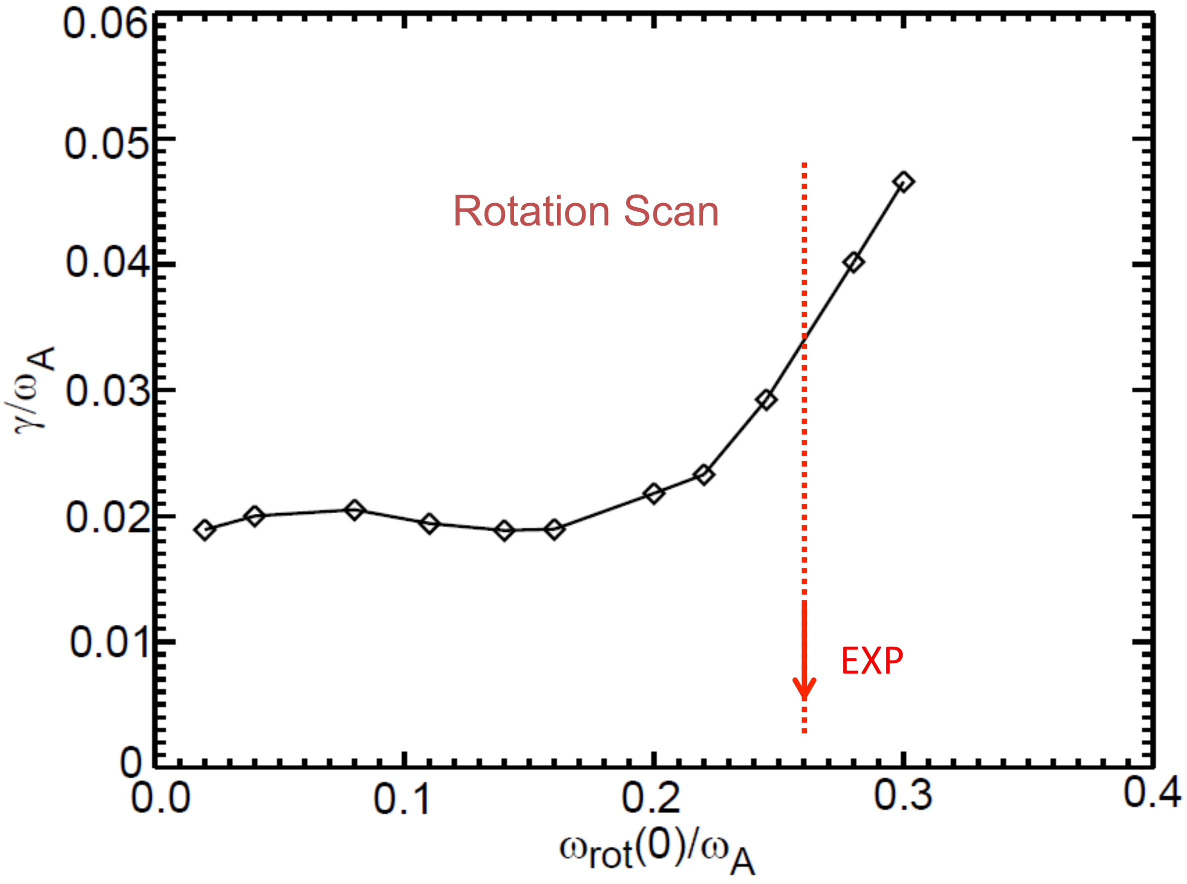
- Reflectometer response (ξ) modeled for M3D-K δn
  - WKB approximation for path length (L) used

$$L = L_0 + \xi = \int_{edge}^{\omega_p^2(R)=\omega^2} \sqrt{1-\omega_p^2(R)/\omega^2}$$

- ξ is mainly determined by density variation near the cut-off layer

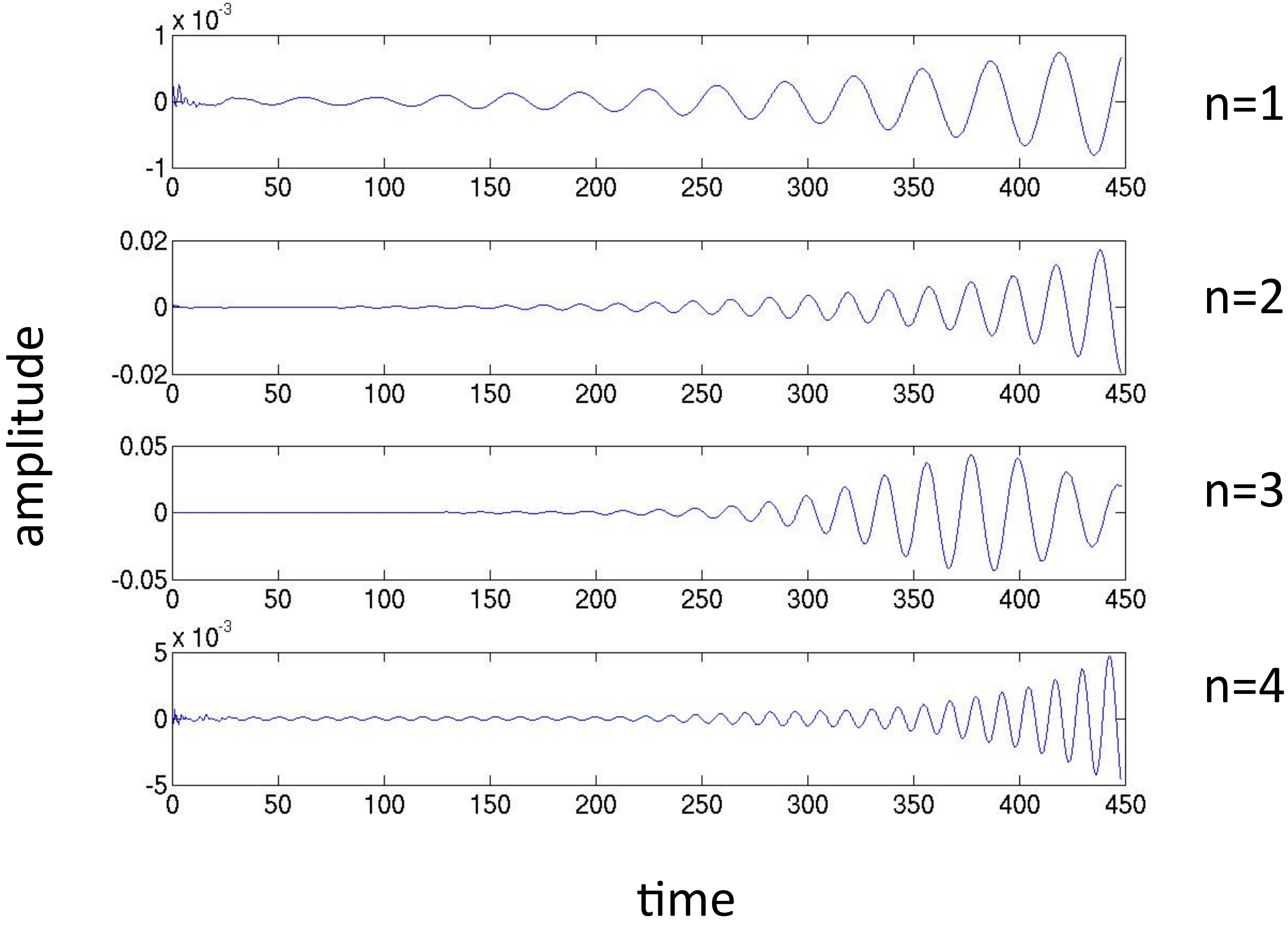
Rotation effect is destabilizing

D. Liu et al, PoP 2015

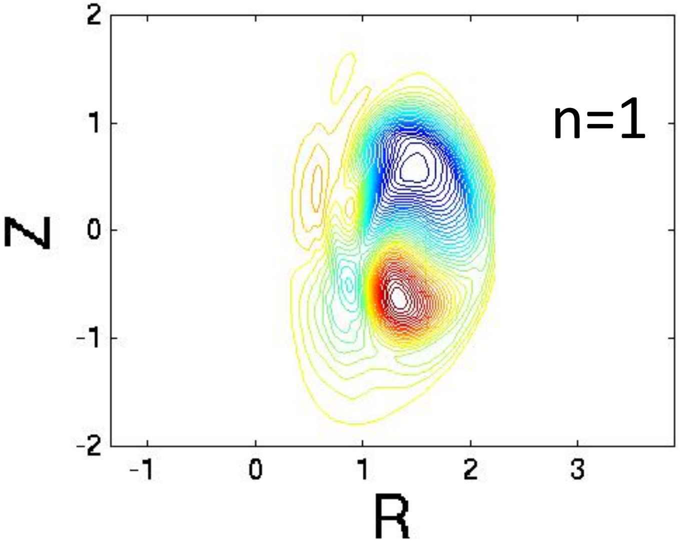


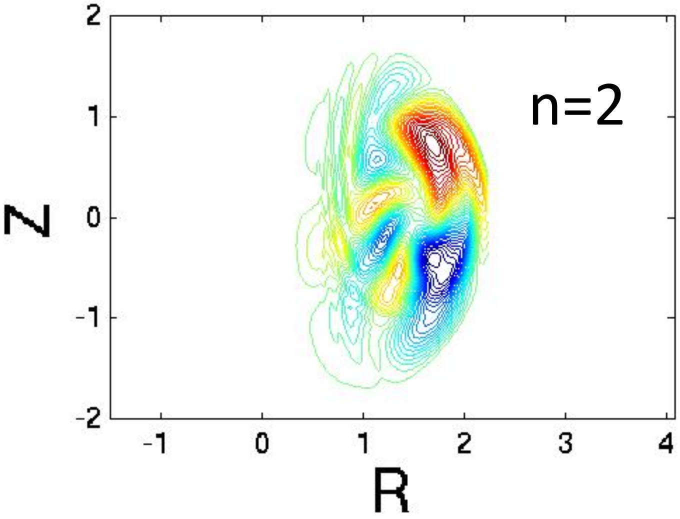
TAE growth rate versus plasma toroidal rotation frequency

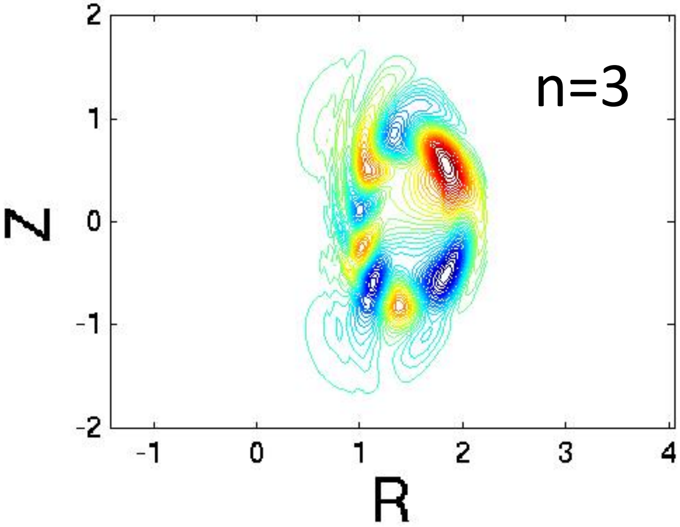
Single mode simulations: amplitude evolution

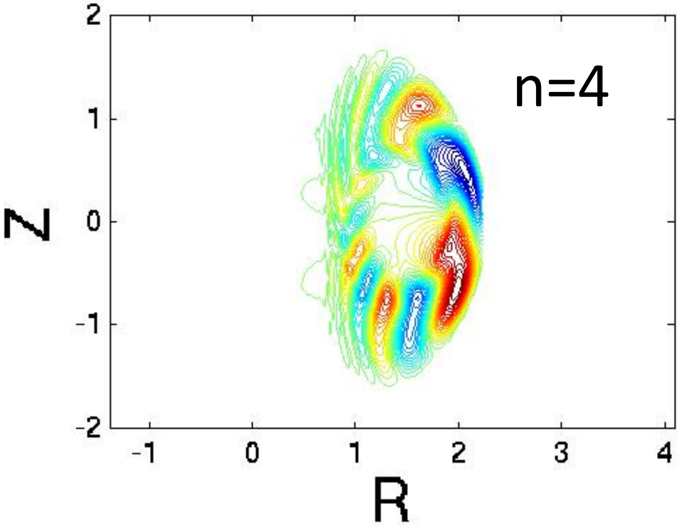


Mode structures

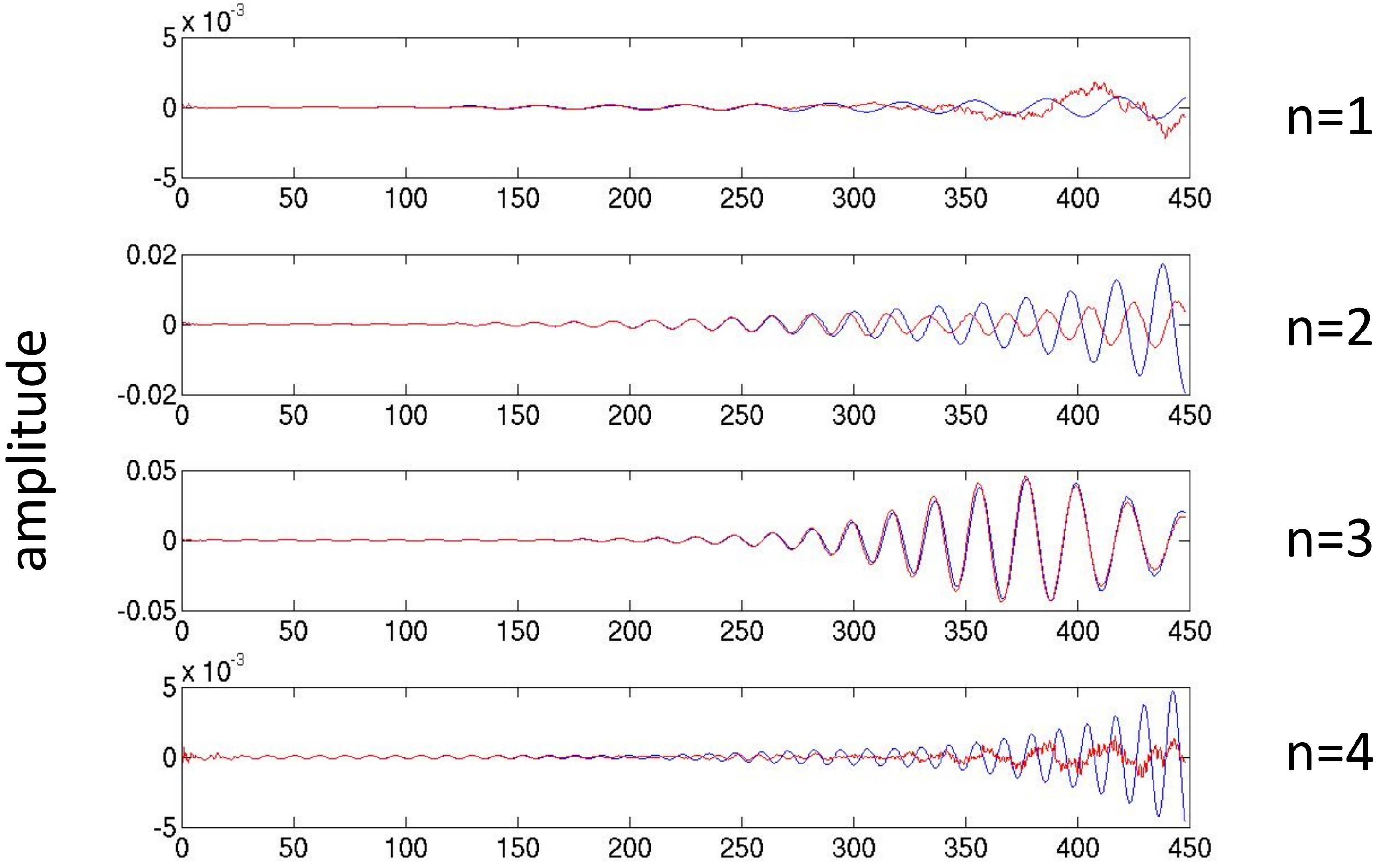








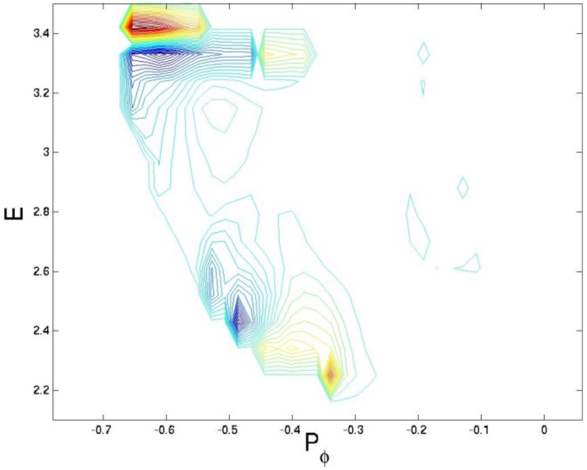
Multi-mode simulation show mode mode interaction via wave particle interaction



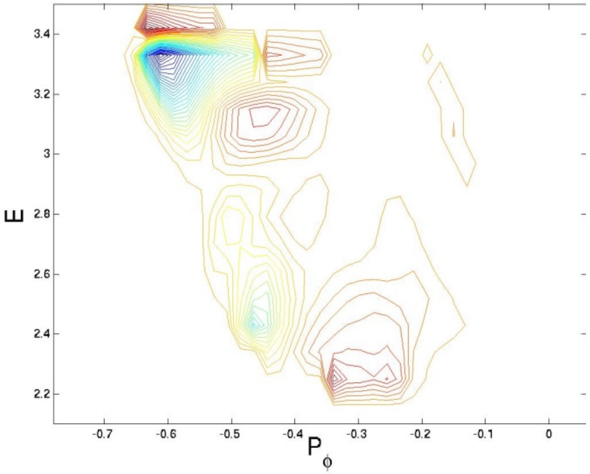
Comparison of mode evolution between single mode simulation (blue) and multi-mode simulation (red)

Structure of perturbed beam ion distribution shows resonance overlap

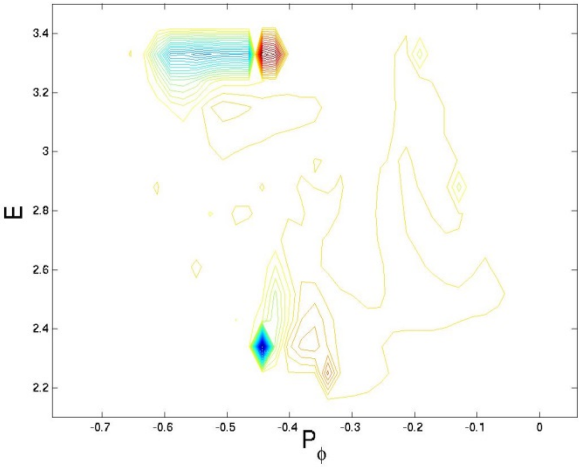
n=2



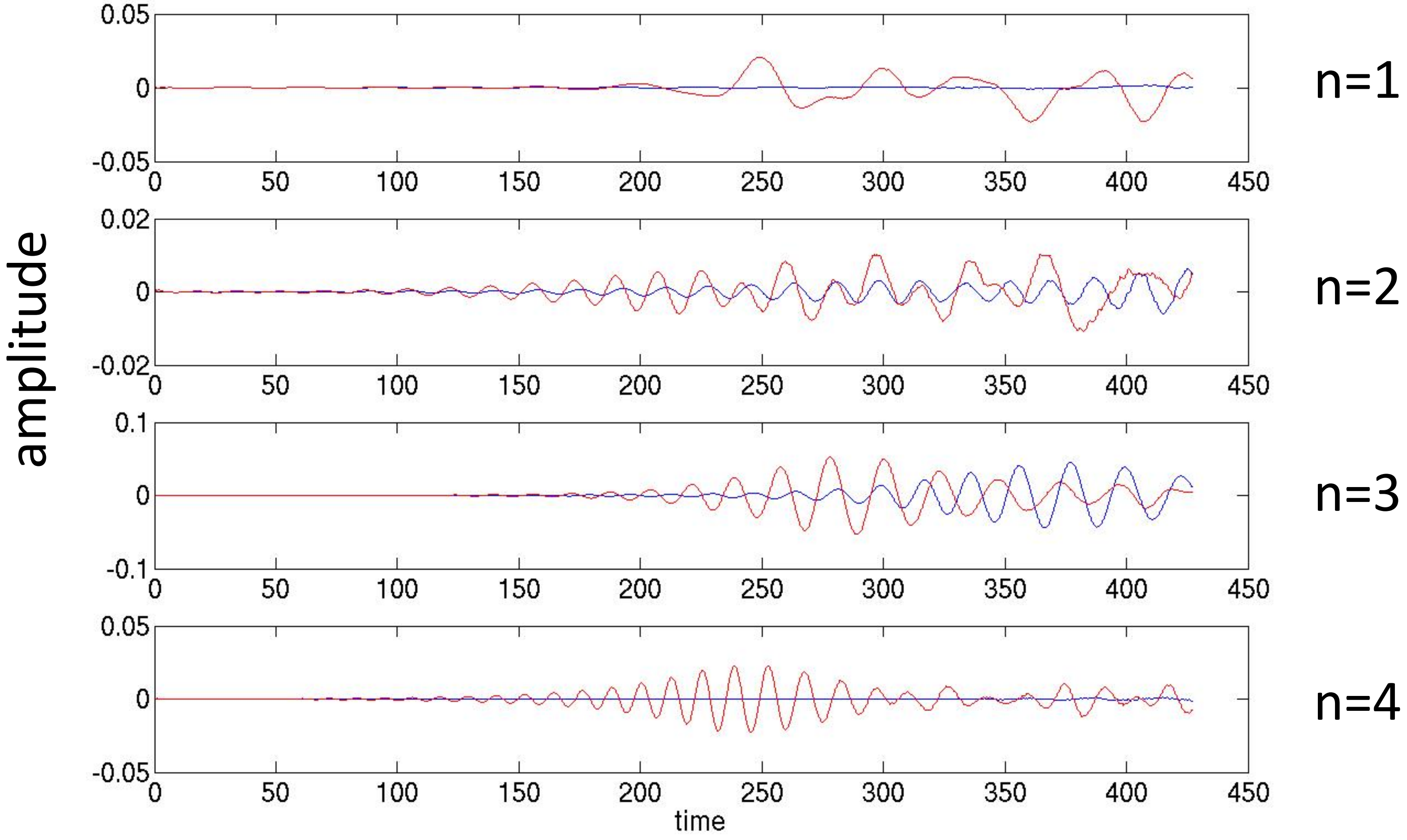
n=3



n=4

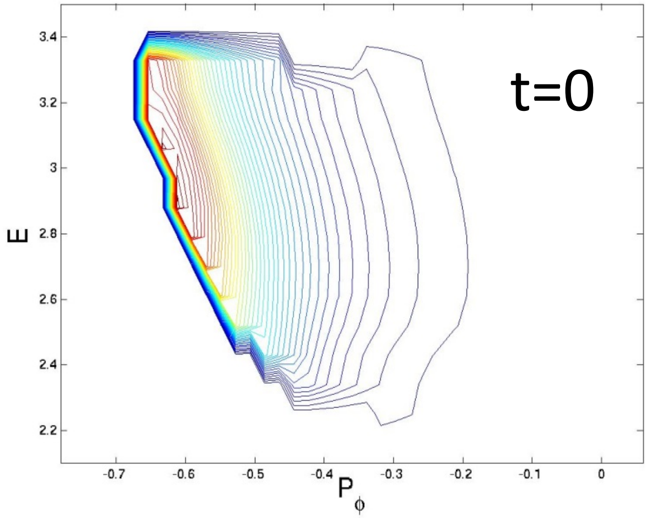


Mode amplitudes increase sharply as beam beta exceeds a threshold

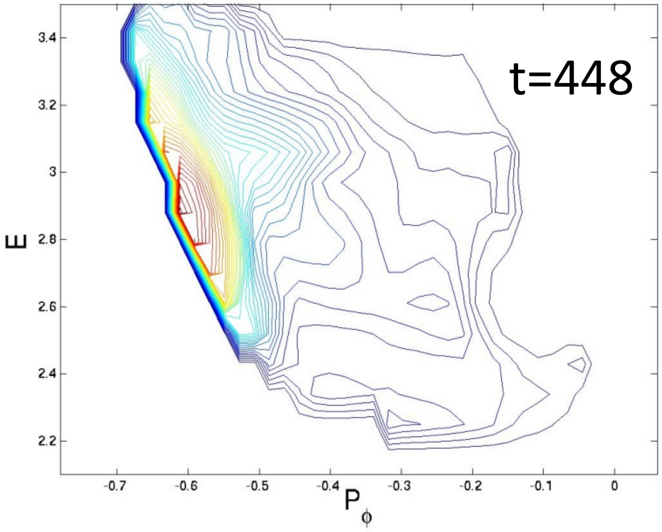


Comparison of mode amplitude evolution between β_h=12% (blue) and β_h=14% (red)

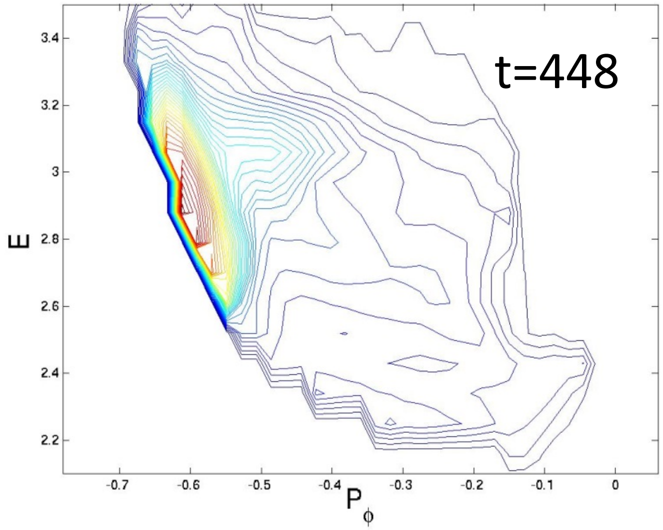
Distribution flattening: global transport when beam beta exceeds a threshold



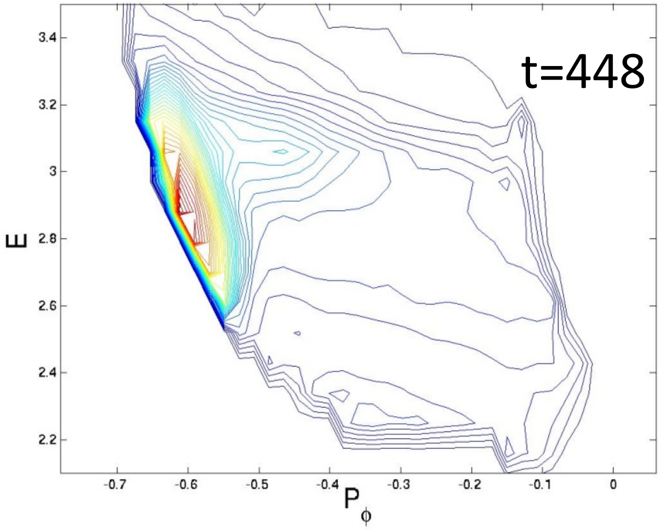
β_h=10%



β_h=12%



β_h=14%



Summary

- Rotation effect is destabilizing for fishbone (higher qmin) and TAEs;
- Fishbone frequency chirping is possibly due to resonant particles moving outward radially keeping resonance with the mode;
- Nonlinear simulation shows strong interaction between multiple TAEs and fishbone due to overlap of resonances;
- Signature of TAE avalanche is observed in the multi-mode simulation:
  - sharp increase in mode amplitude as beam beta exceeds a threshold;
  - global particle transport due to overlap of resonances.