Nonlinear Dynamics of Beam-driven TAEs in NSTX

G.Y. Fu*, F. Wang*

Princeton Plasma Physics Laboratory

D.Y. Liu

Univ. of California, Irvine

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

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Outline

1. Introduction

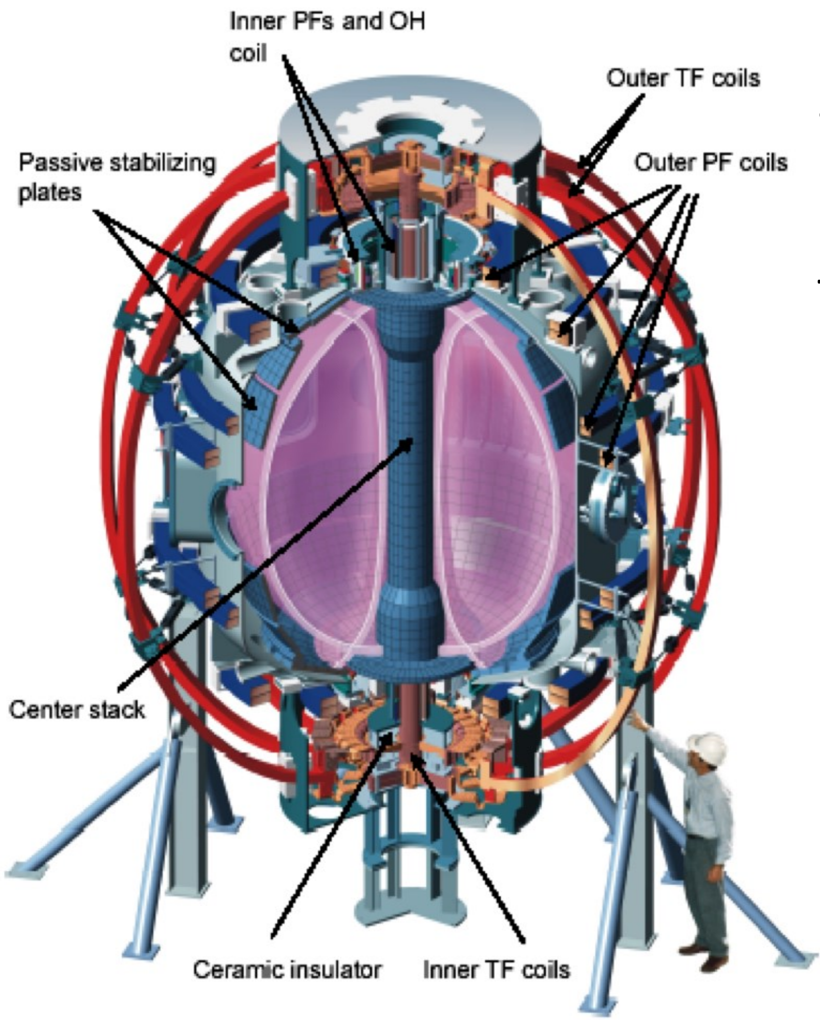
2. Beam-driven TAEs in NSTX

3. Conclusions

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

National Spherical Tokamak eXperiment (NSTX)

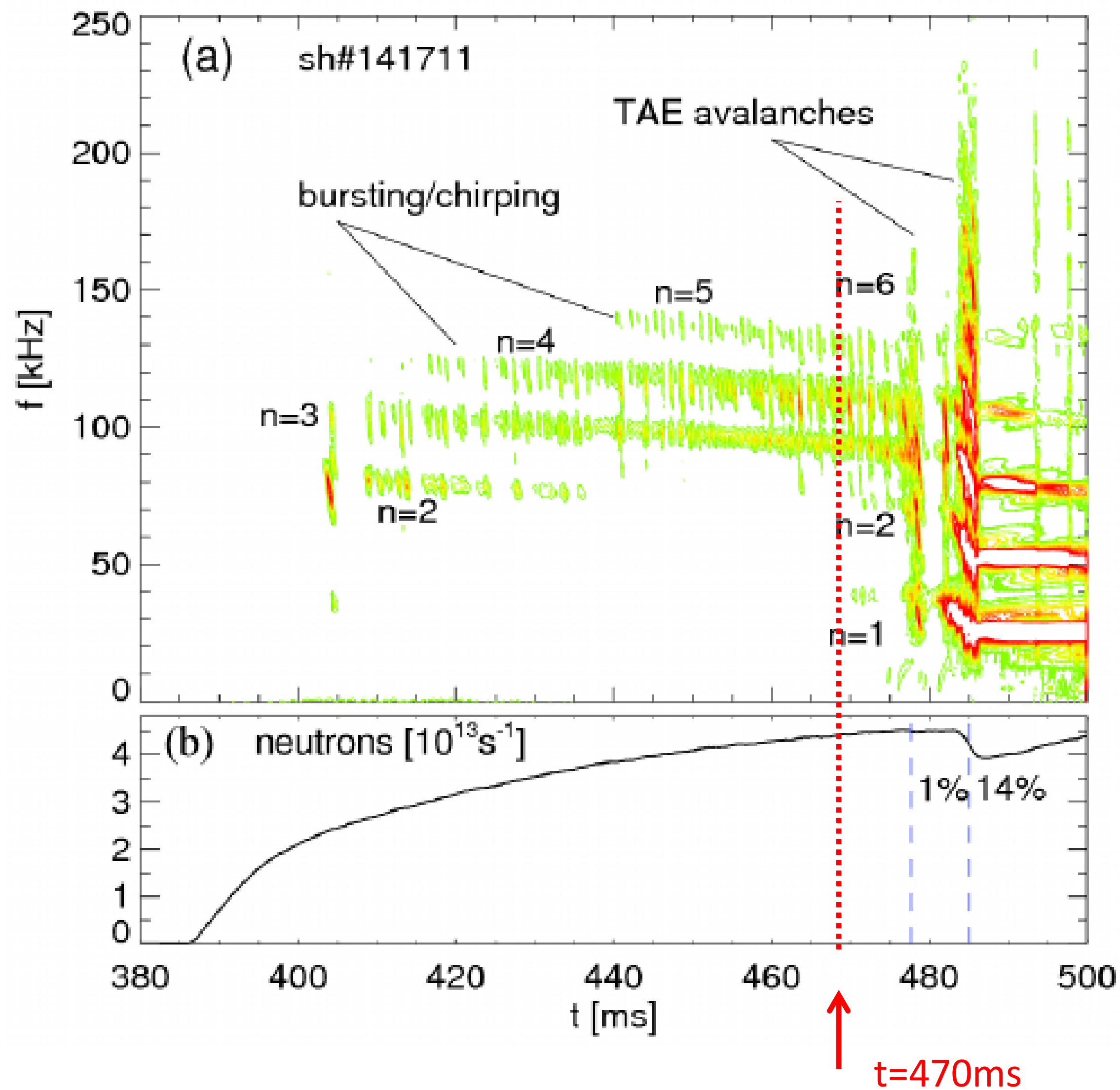


NSTX is a spherical tokamak operated at Princeton Plasma physics Lab from 1999 to about 2013. It is being upgraded at present.

It was heated by Neutral Beam Injection.
The energetic beam ions can excite many Instabilities such as fishbone, TAEs, CAE/GAE etc.

$R \sim 0.87m$
$a \sim 0.60m$
$B \sim 0.5T$
$\beta_{beam} \sim \beta_{thermal} \sim 0.15$

Beam-driven TAEs are routinely observed in NSTX.



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

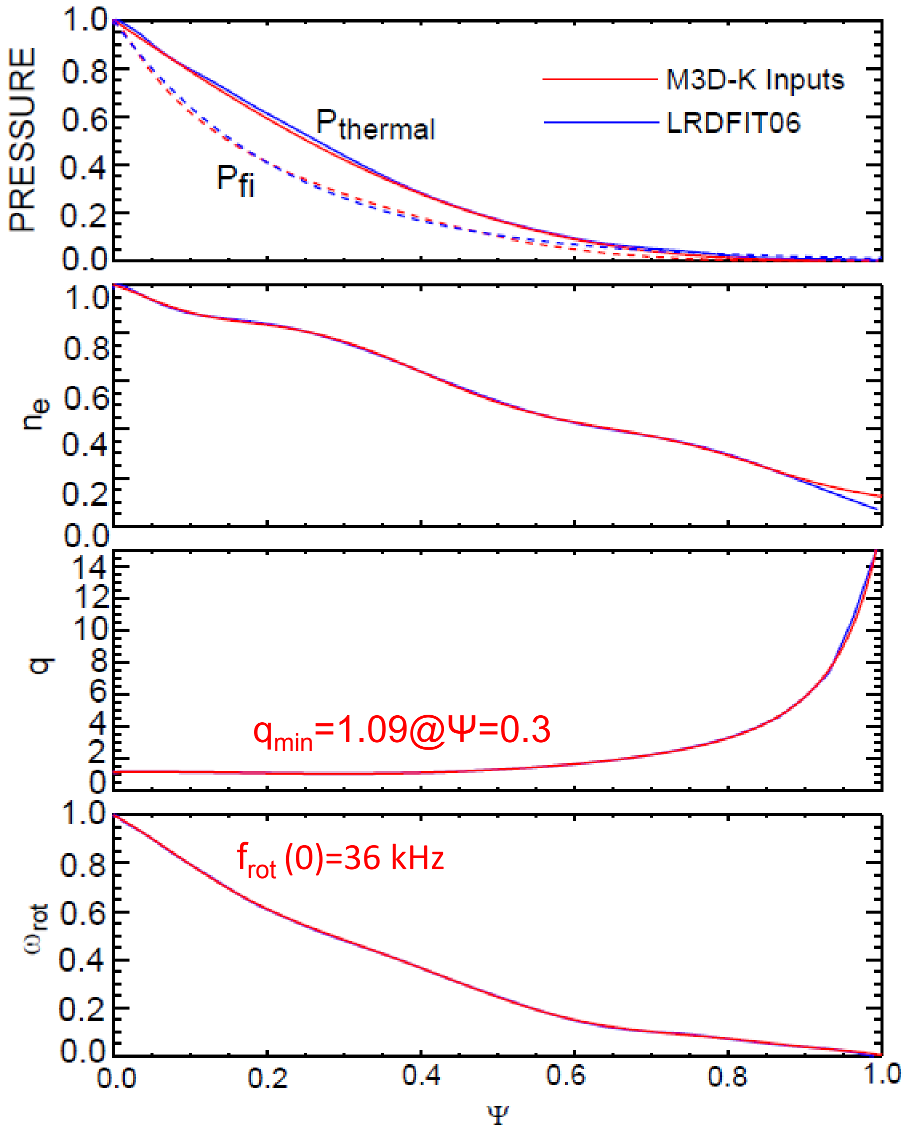
$$\rho \frac{d\mathrm{v}}{dt} = -\nabla P_{th} - \nabla \cdot P_h + J \times B \qquad \frac{dP_{th}}{dt} = -\gamma P_{th} \nabla \cdot \mathrm{v}$$

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

*The energetic particle stress tensor, P_h, is calculated by solving drift kinetic or gyrokinetic equation using PIC method.
*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)

Experimental Plasma Parameters and Profiles are Used for TAE Simulation



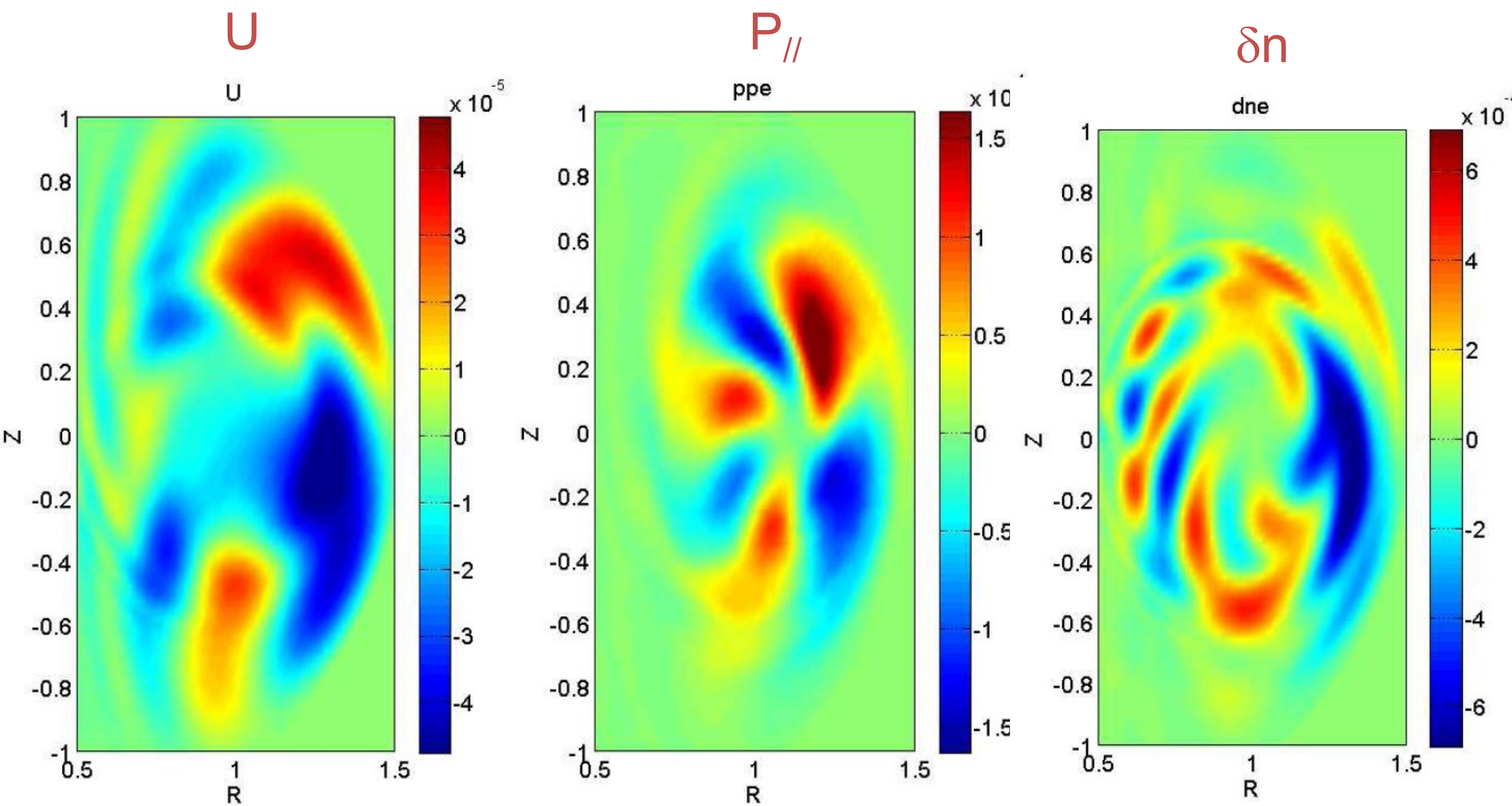
- ➢NSTX parameters (B_0 =0.55T, R=0.85m, a=0.67m) and equilibrium profiles at 470 ms of shot 141711
  - $n_e(0)$=4.4x 10^{13} cm^{-3}
  - $T_e(0)$=1.4 keV
  - $T_i(0)$=1.3 keV

- ➢ 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

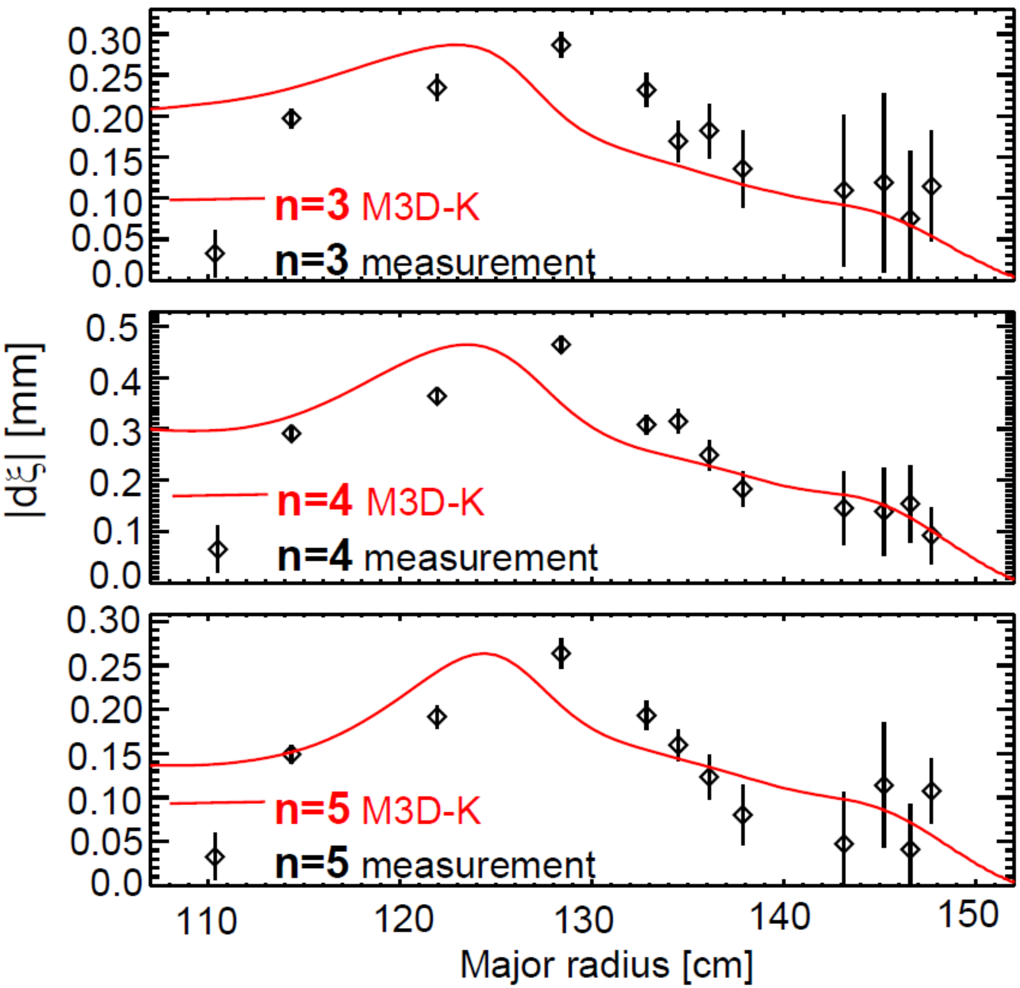
$$f = \frac{cH(v_0 - v)}{v^3 + v_c^3} \exp(-\psi / \Delta\psi) \exp[-(\Lambda - \Lambda_0)^2 / \Delta\Lambda^2], \Lambda = \frac{\mu B}{E}$$

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

n=3 Simulation Exhibits TAE-like Global Feature



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

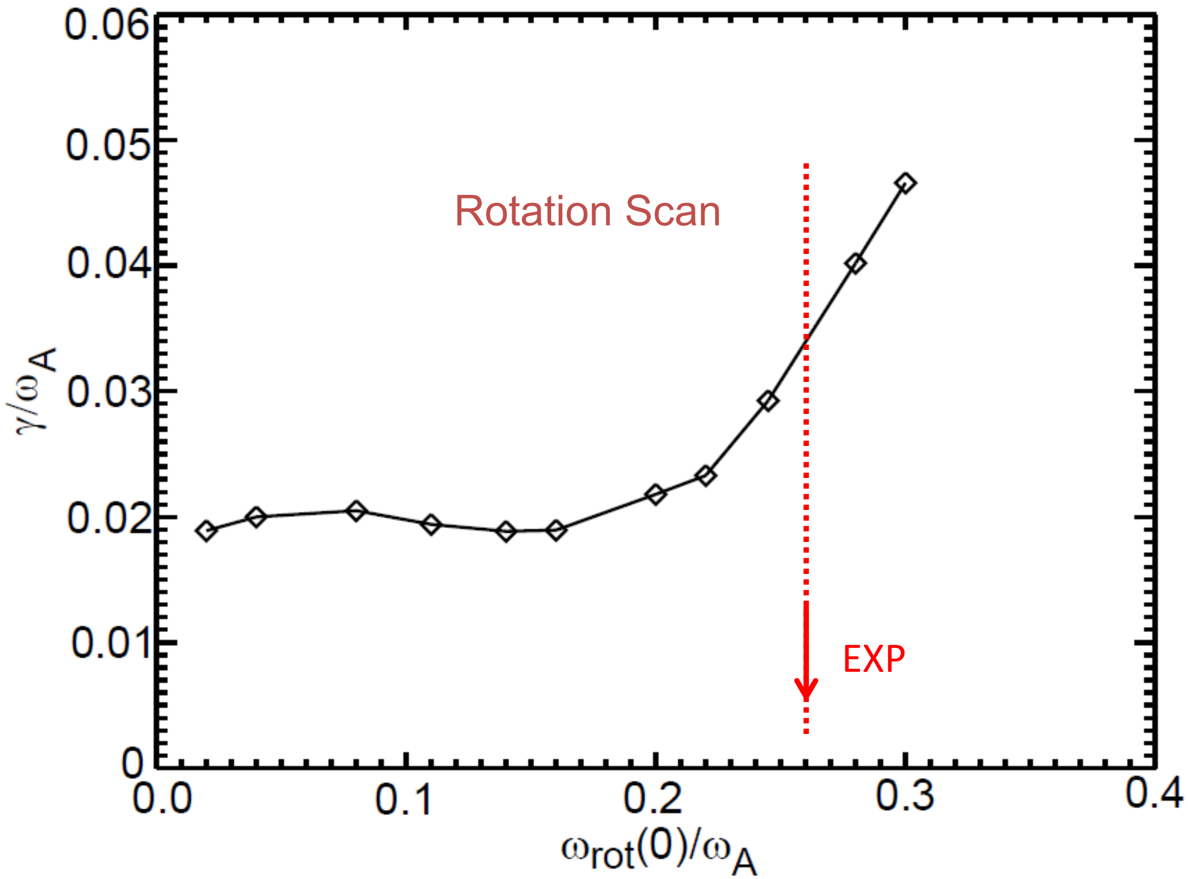
- Reflectometer response (ξ) modeled for M3D-K δn
  - WKB approximation for path length (L) used

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

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

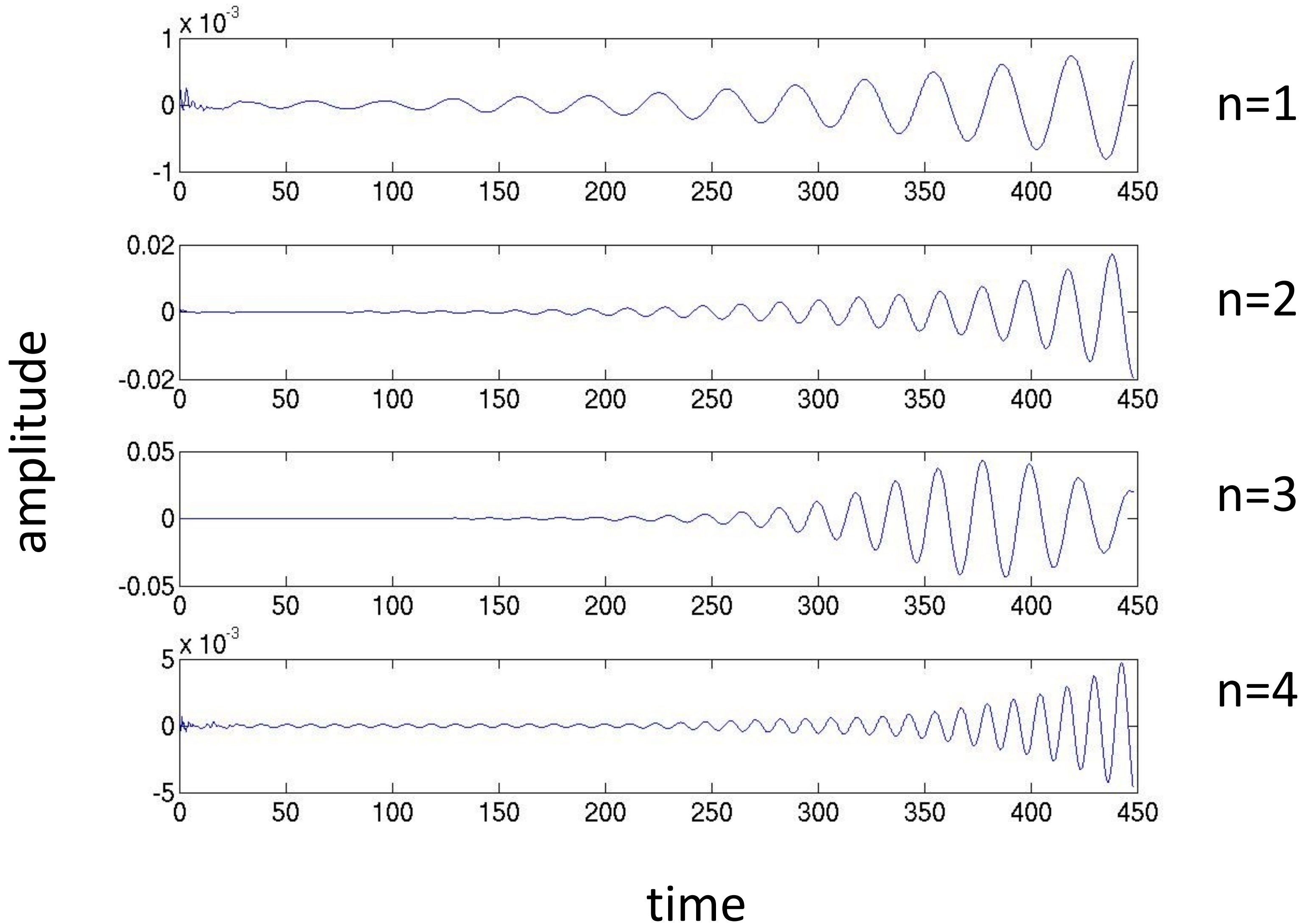
Rotation effect is destabilizing

D. Liu et al, PoP 2015

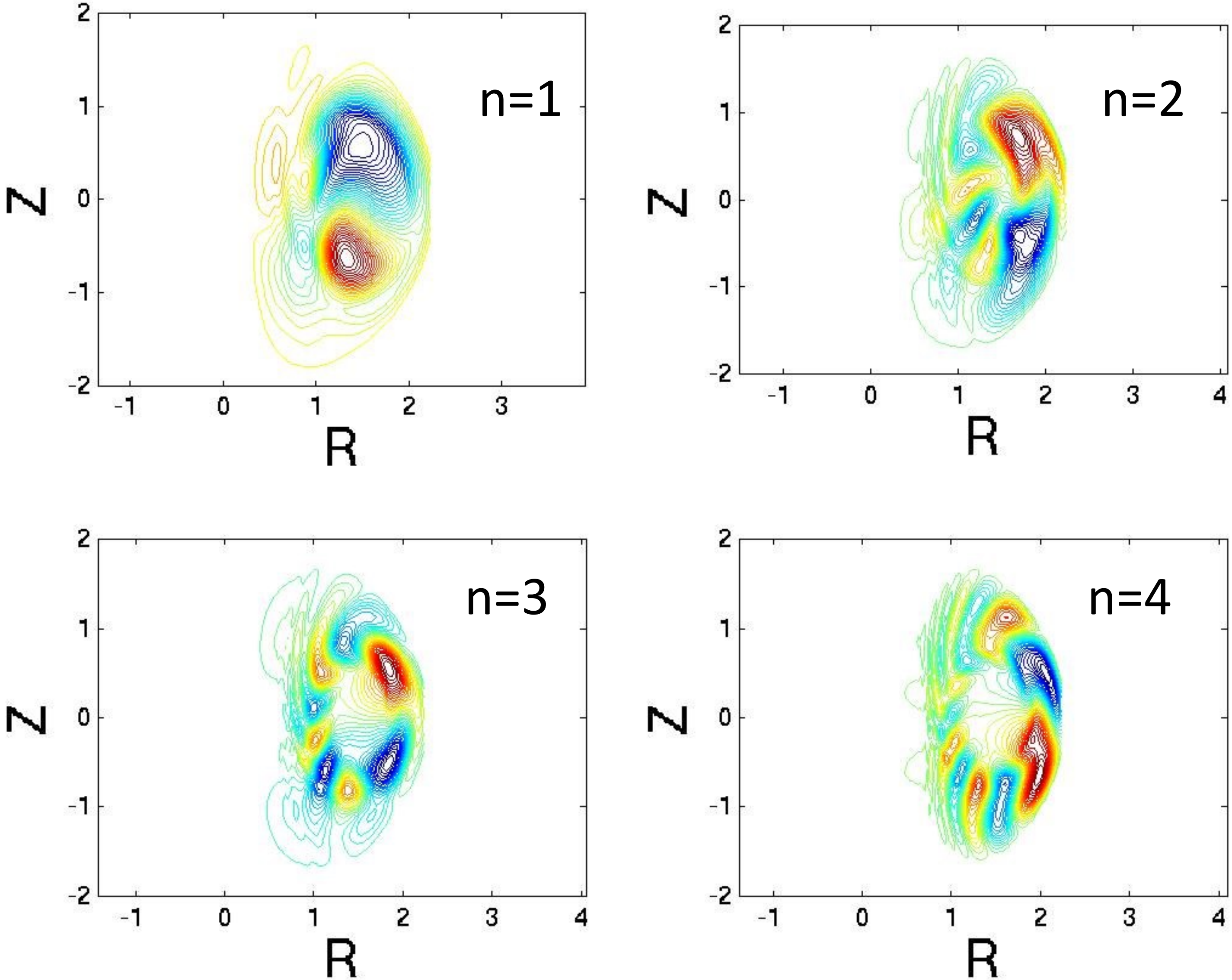


TAE growth rate versus plasma toroidal rotation frequency

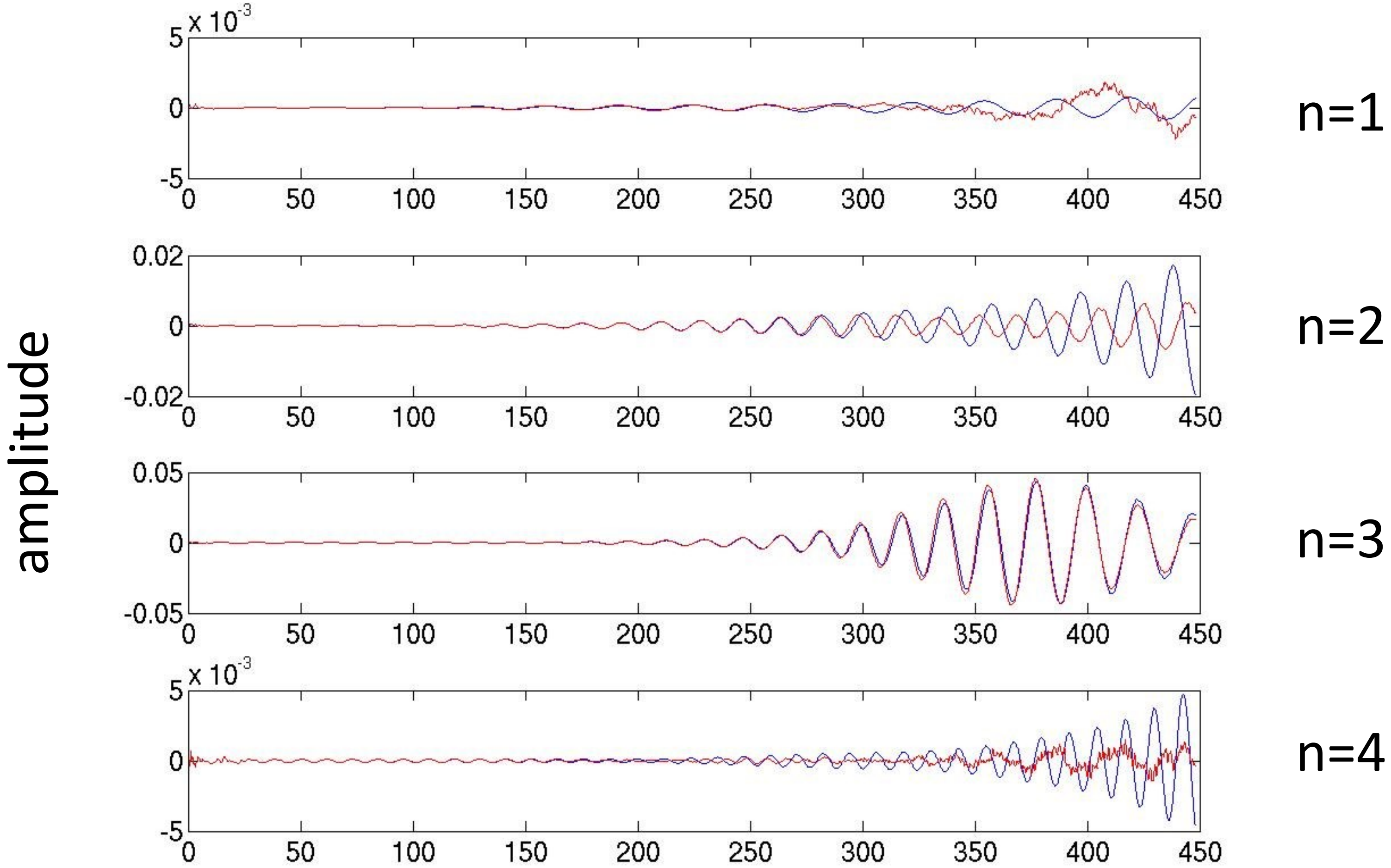
Single mode simulations: amplitude evolution



Mode structures



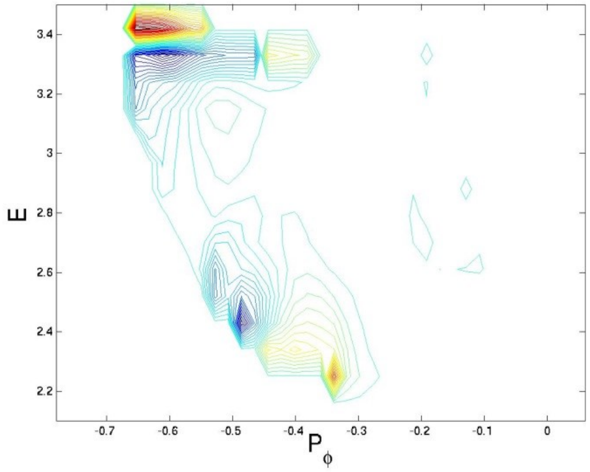
Multi-mode simulation show mode mode interaction via wave particle interaction



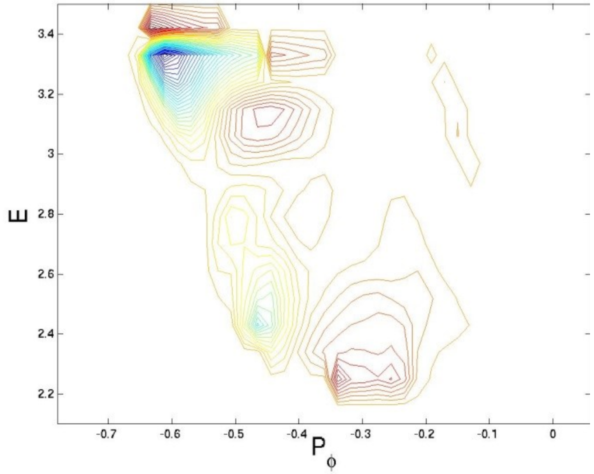
Comparison of mode evolution between single mode simulation (blue) and multi-mode simulation (red)

Structure of perturbed beam ion distribution shows resonance overlap

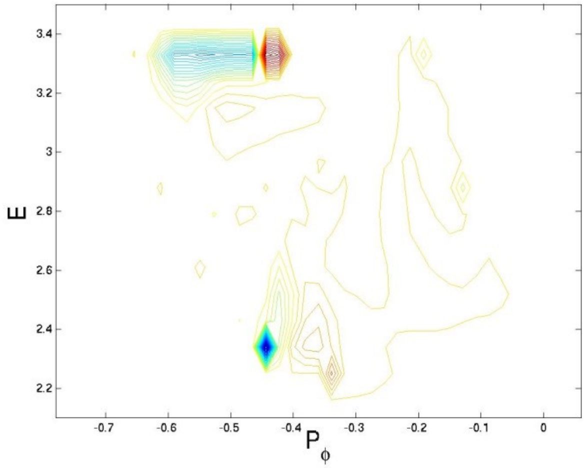
n=2

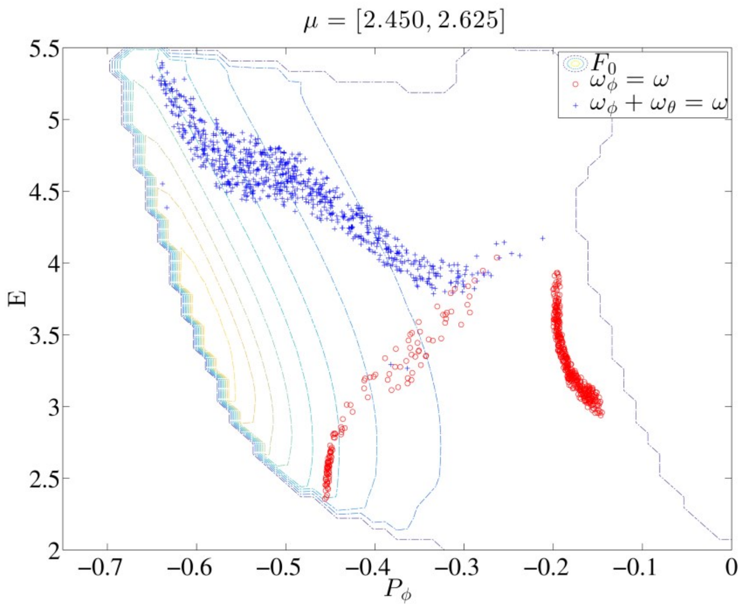


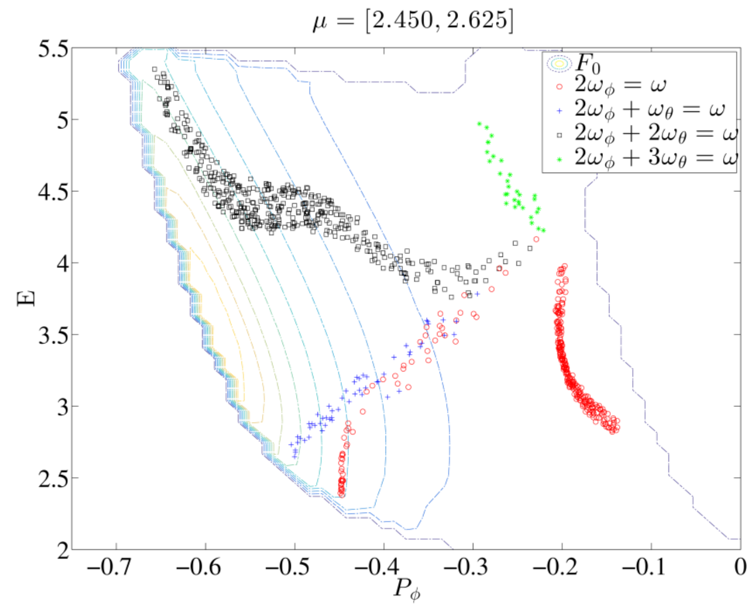
n=3

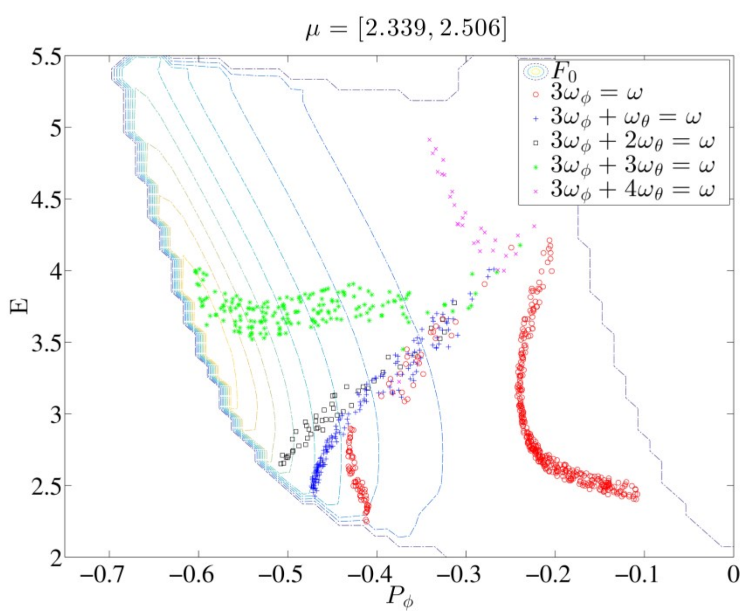


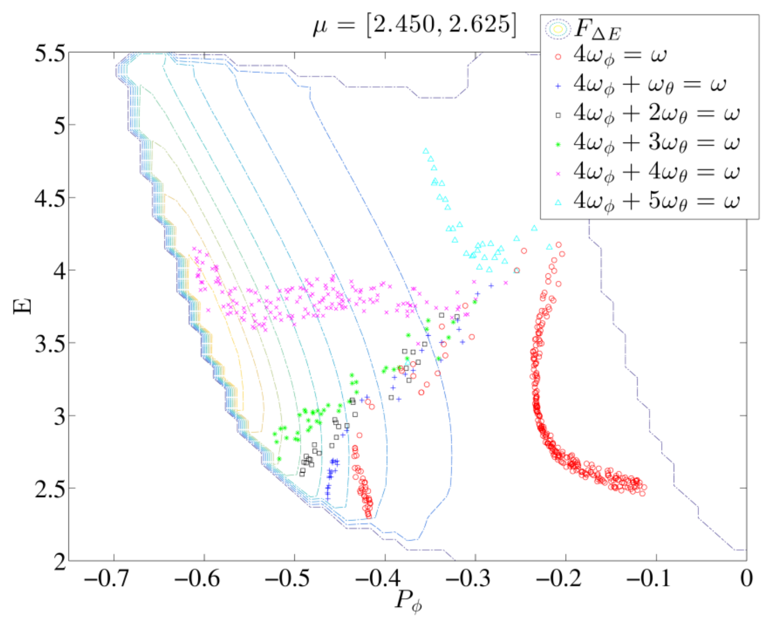
n=4



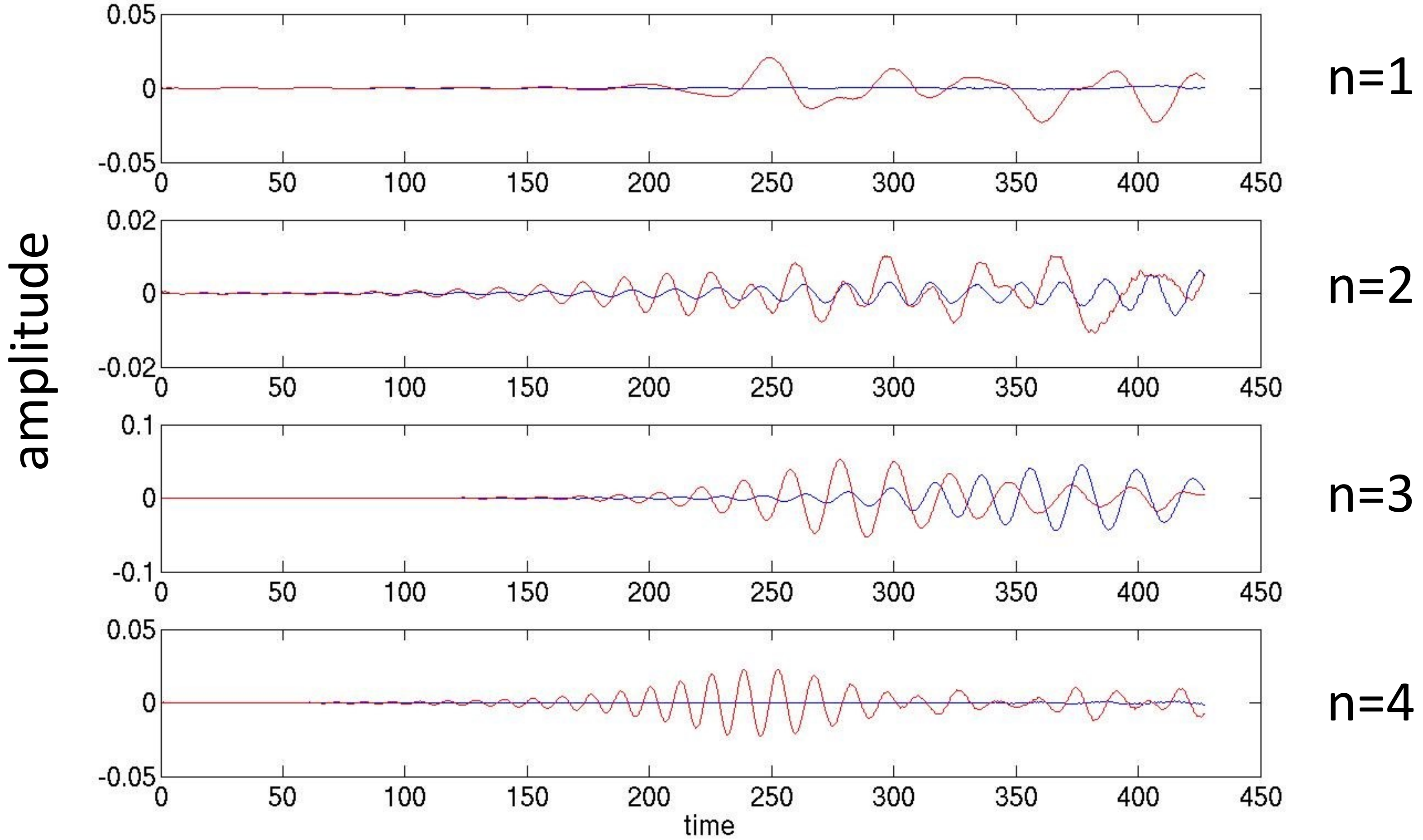

$\mu = [2.450, 2.625]$
F_0
$\omega_\phi = \omega$
$\omega_\phi + \omega_\theta = \omega$
E
P_ϕ
5.5 5 4.5 4 3.5 3 2.5 2
−0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0


$\mu = [2.450, 2.625]$
F_0
$2\omega_\phi = \omega$
$2\omega_\phi + \omega_\theta = \omega$
$2\omega_\phi + 2\omega_\theta = \omega$
$2\omega_\phi + 3\omega_\theta = \omega$
E
P_ϕ
5.5 5 4.5 4 3.5 3 2.5 2
−0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0


$\mu = [2.339, 2.506]$
F_0
$3\omega_\phi = \omega$
$3\omega_\phi + \omega_\theta = \omega$
$3\omega_\phi + 2\omega_\theta = \omega$
$3\omega_\phi + 3\omega_\theta = \omega$
$3\omega_\phi + 4\omega_\theta = \omega$
E
P_ϕ
5.5 5 4.5 4 3.5 3 2.5 2
−0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0

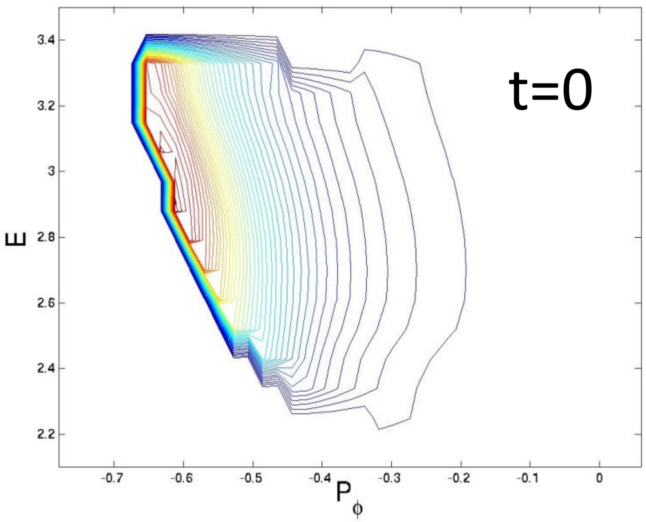

$\mu = [2.450, 2.625]$
$F_{\Delta E}$
$4\omega_\phi = \omega$
$4\omega_\phi + \omega_\theta = \omega$
$4\omega_\phi + 2\omega_\theta = \omega$
$4\omega_\phi + 3\omega_\theta = \omega$
$4\omega_\phi + 4\omega_\theta = \omega$
$4\omega_\phi + 5\omega_\theta = \omega$
E
P_ϕ
5.5 5 4.5 4 3.5 3 2.5 2
−0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0

Mode amplitudes increase sharply as beam beta exceeds a threshold

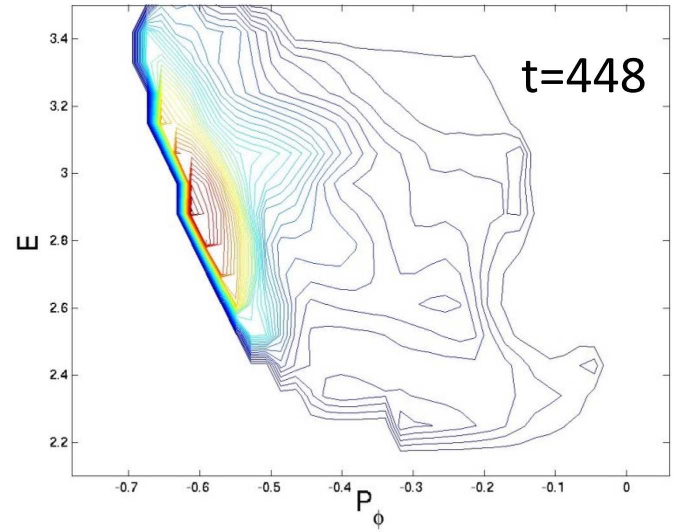


Comparison of mode amplitude evolution between β_h=12% (blue) and β_h=14% (red)

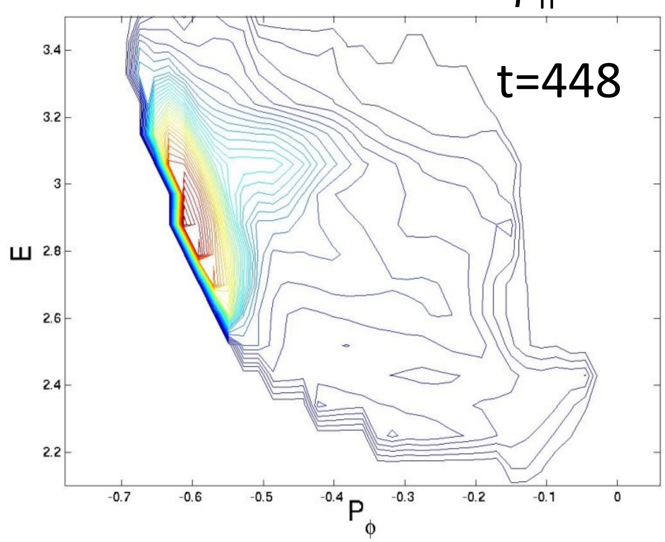
Distribution flattening: global transport when beam beta exceeds a threshold



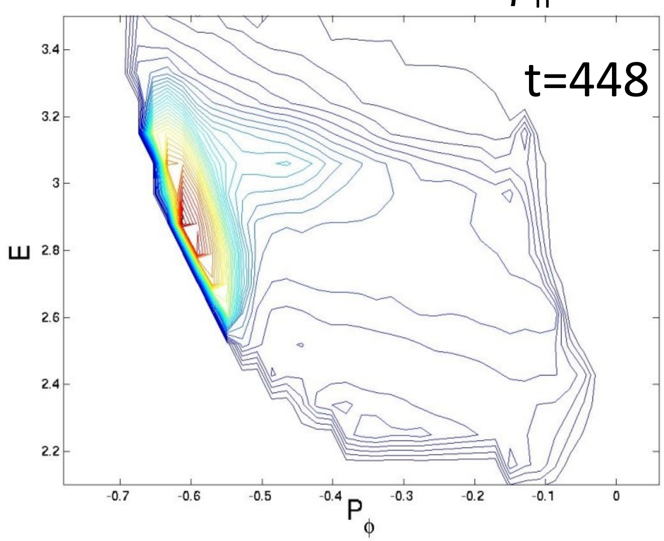
β_h=10%



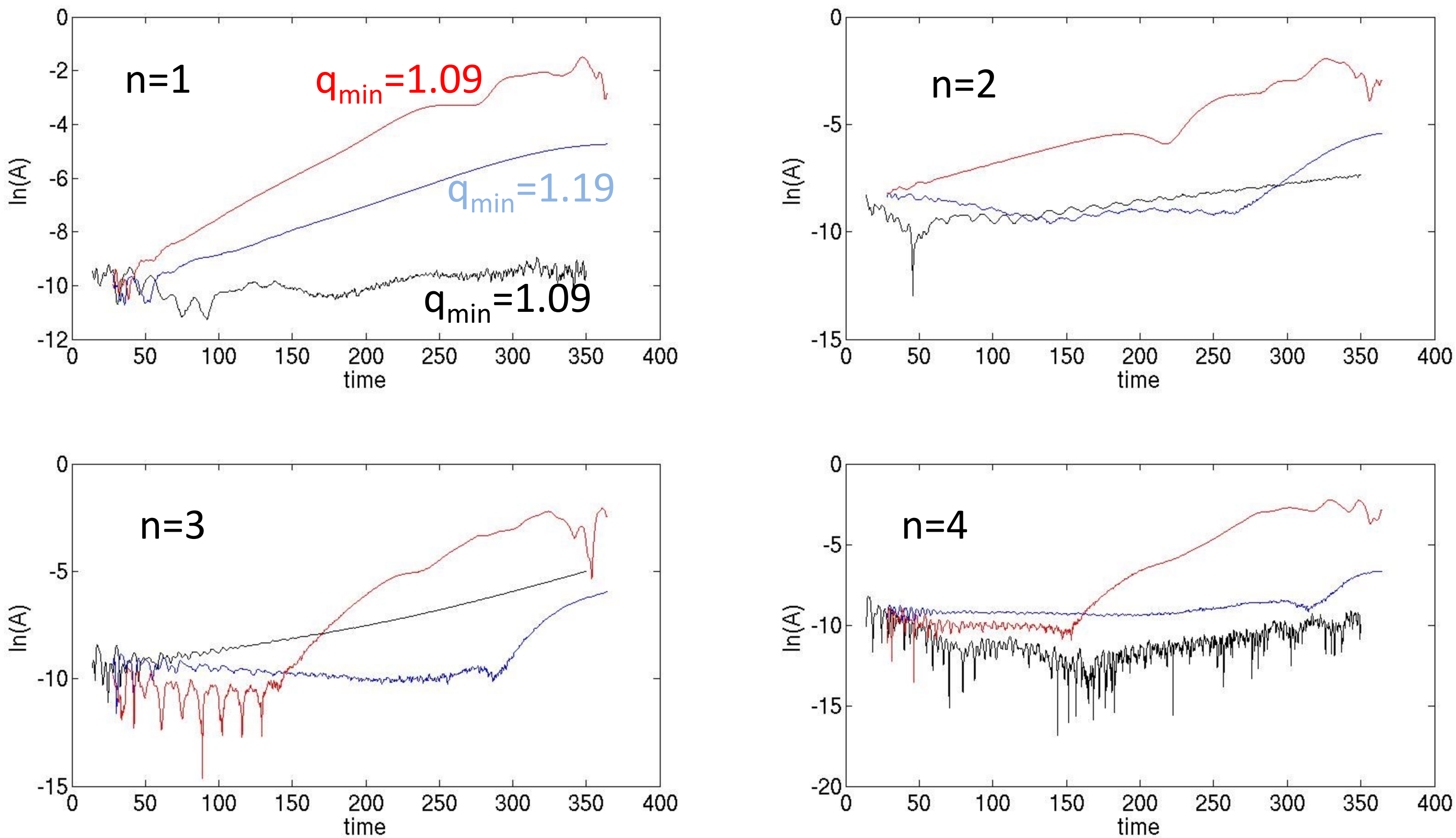
β_h=12%



β_h=14%



Mode saturation levels increase sharply as q_{min} drops from 1.29 to 1.09



Summary

- Rotation effect is destabilizing for TAEs;
- 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 or as q_{min} drops below a threshold.

global particle transport due to overlap of resonances.