PRINCETON PLASMA PHYSICS LABORATORY

Nonlinear Fishbone Dynamics in Spherical Tokamaks with Toroidal Rotation

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Outline

1. Motivation and Introduction

2. Fishbone linear stability with toroidal rotation

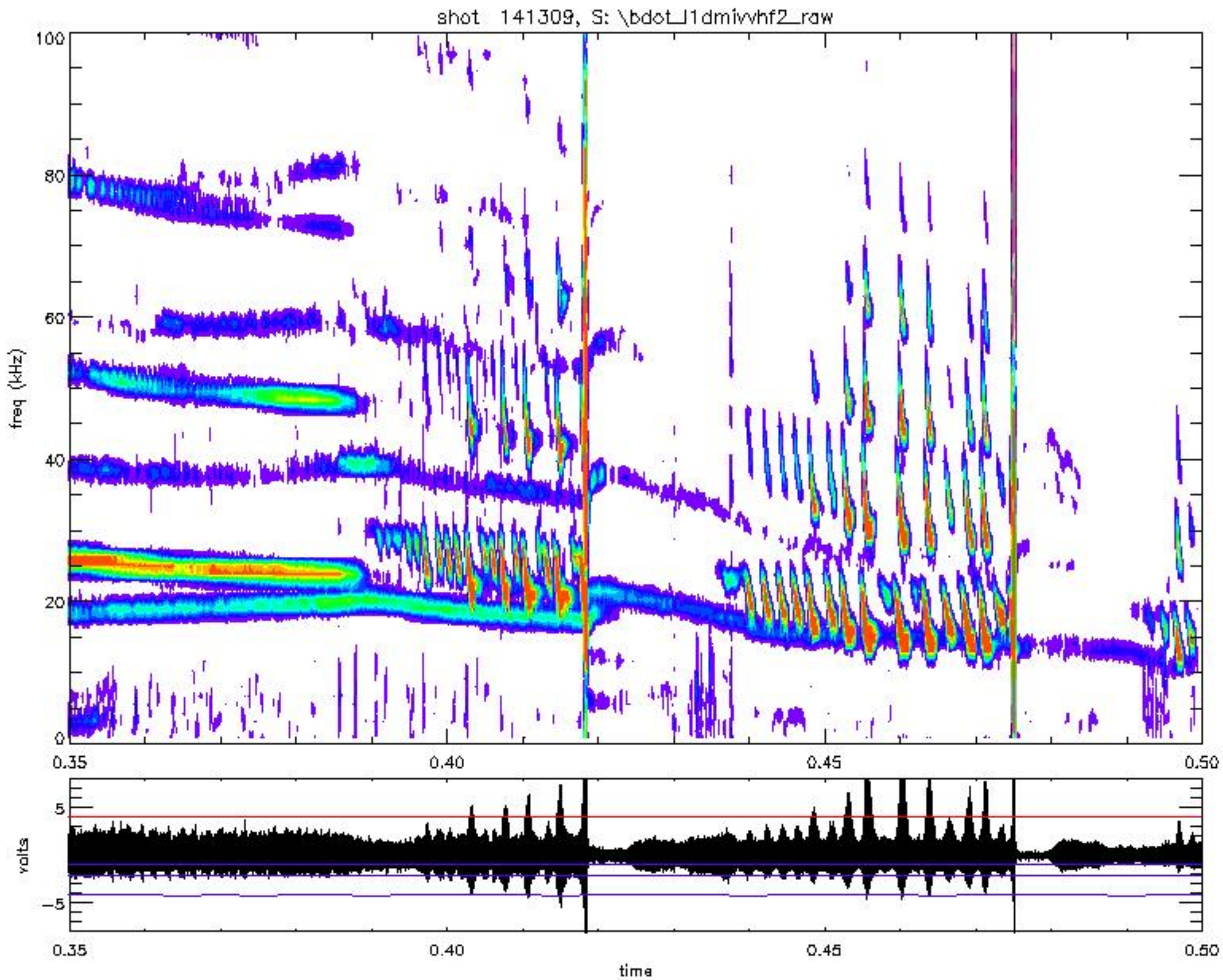
3. Fishbone nonlinear dynamics

4. Conclusions

Motivation

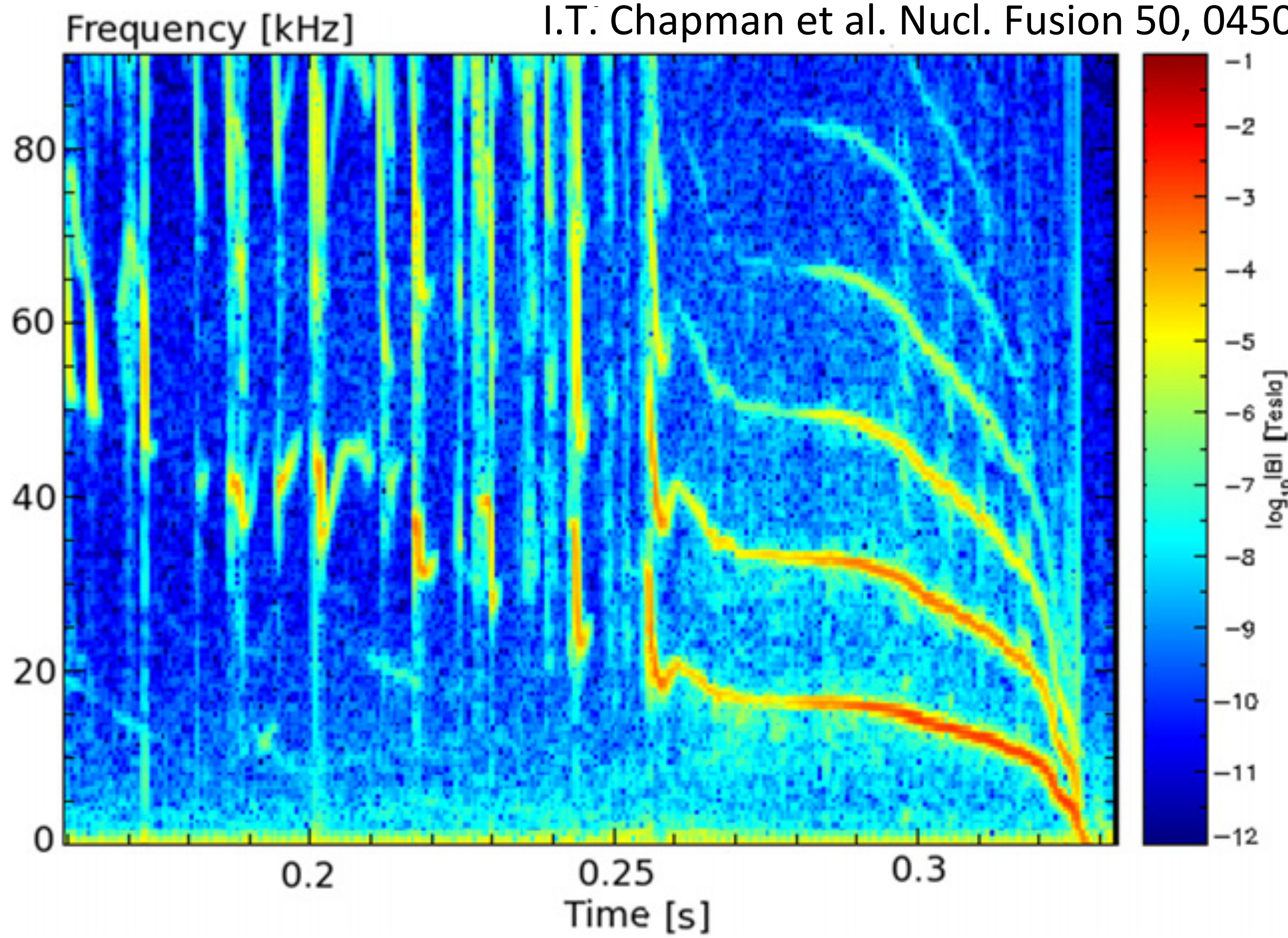
- Energetic particle (EP)-driven instabilities can induce significant alpha particle redistribution and losses to the first wall of fusion reactors.
- Energetic particle can interact with thermal plasma strongly: affect equilibrium, stability and transport. EP physics is a key element for understanding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

Beam-driven fishbone instability is routinely observed in NSTX



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

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



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 gyro-kinetic 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)

Linear stability and nonlinear dynamics of the fishbone mode in spherical tokamaks: previous results

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

- We considered 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. Rotational effects were neglected.

- M3D-K simulation results showed that both NRK and fishbone can be unstable in such profile. A fishbone instability preferentially excited at higher $q_{min,}$ which consistent with the observed appearance of the fishbone before the "long-loved mode" in MAST and NSTX experiments.

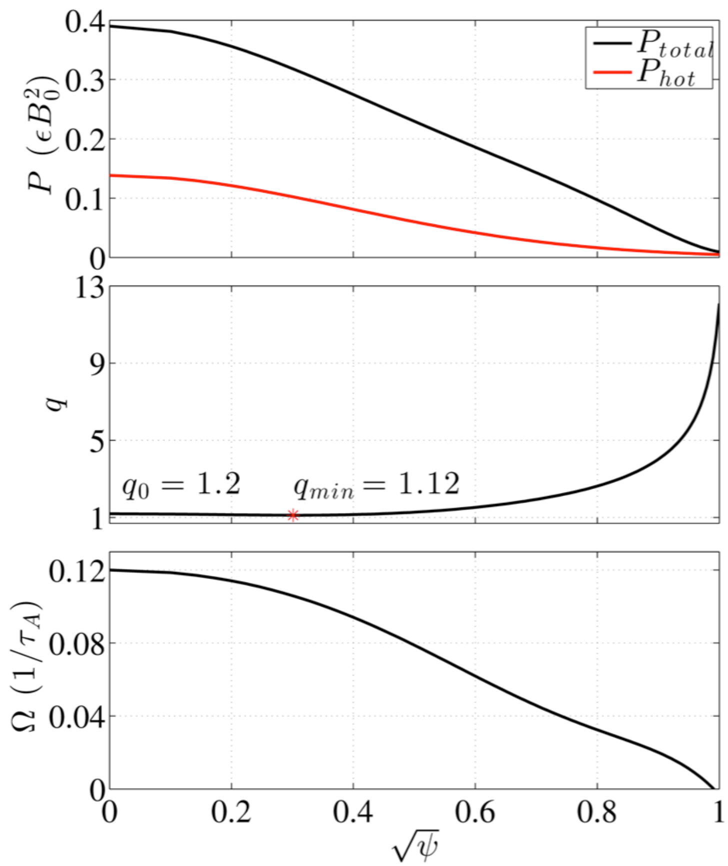
- Nonlinear simulations showed that an m/n=2/1 magnetic island is found to be driven by the fishbone instability, which could provide a trigger for the NTM.

New results in this work

- Effects of toroidal rotation on linear stability.

- Nonlinear phase space dynamics associated with frequency chirping down.

Equilibrium profile and parameters



NSTX #124379 at t=0.635s

B_0=0.44T, R=0.86m, a=0.60m
$n_e(0)$=9.3 x 10^{13} cm^{-3}
$\beta_{tot}(0)$=30%
Analytic fast ion distribution (slowing down)

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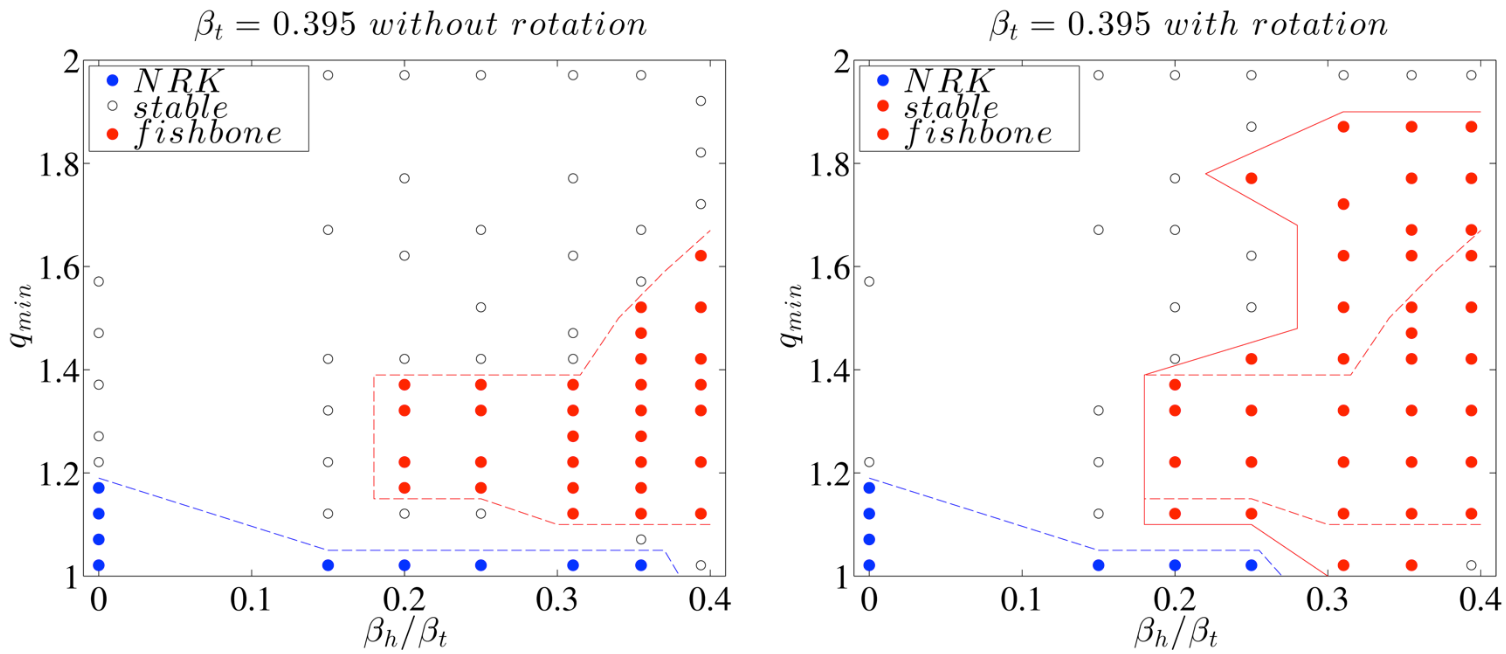
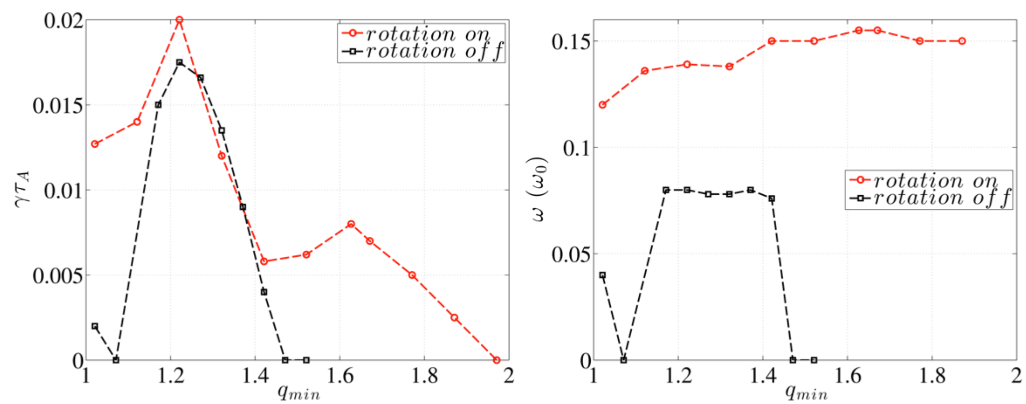
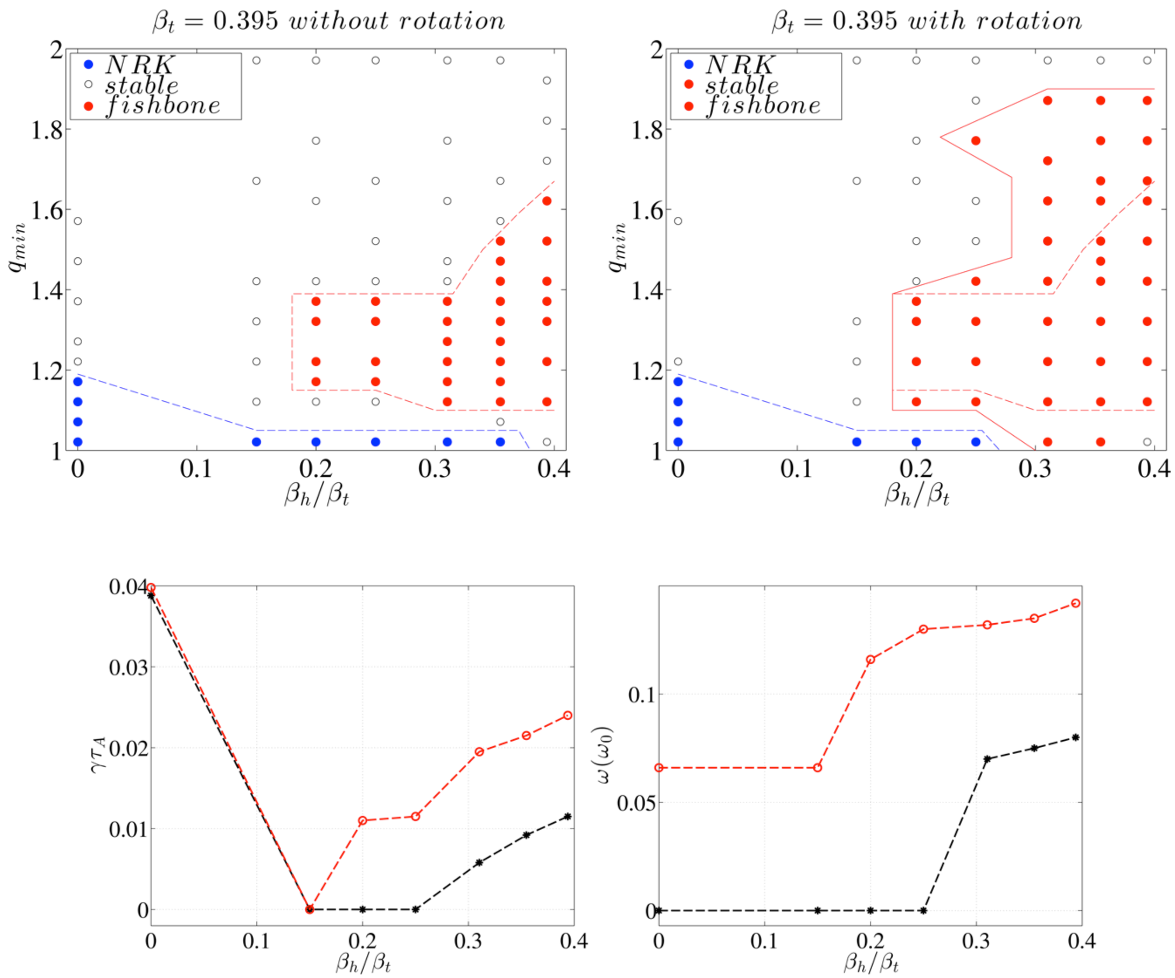
Rotation effect is destabilizing for fishbone at higher q_{min} .





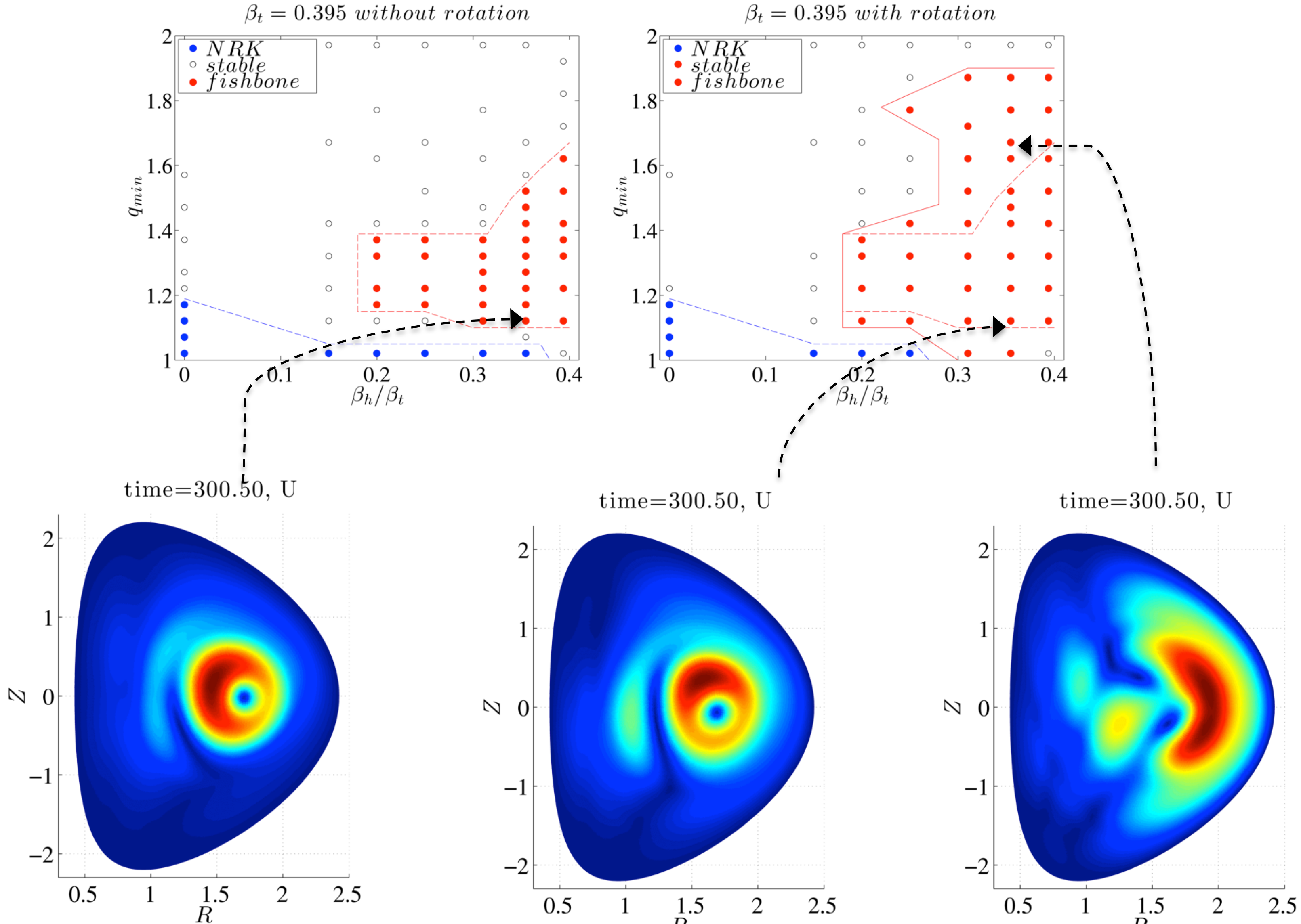
β_h/β_t=0.35

Rotation effect is also destabilizing for fishbone at lower q_{min}

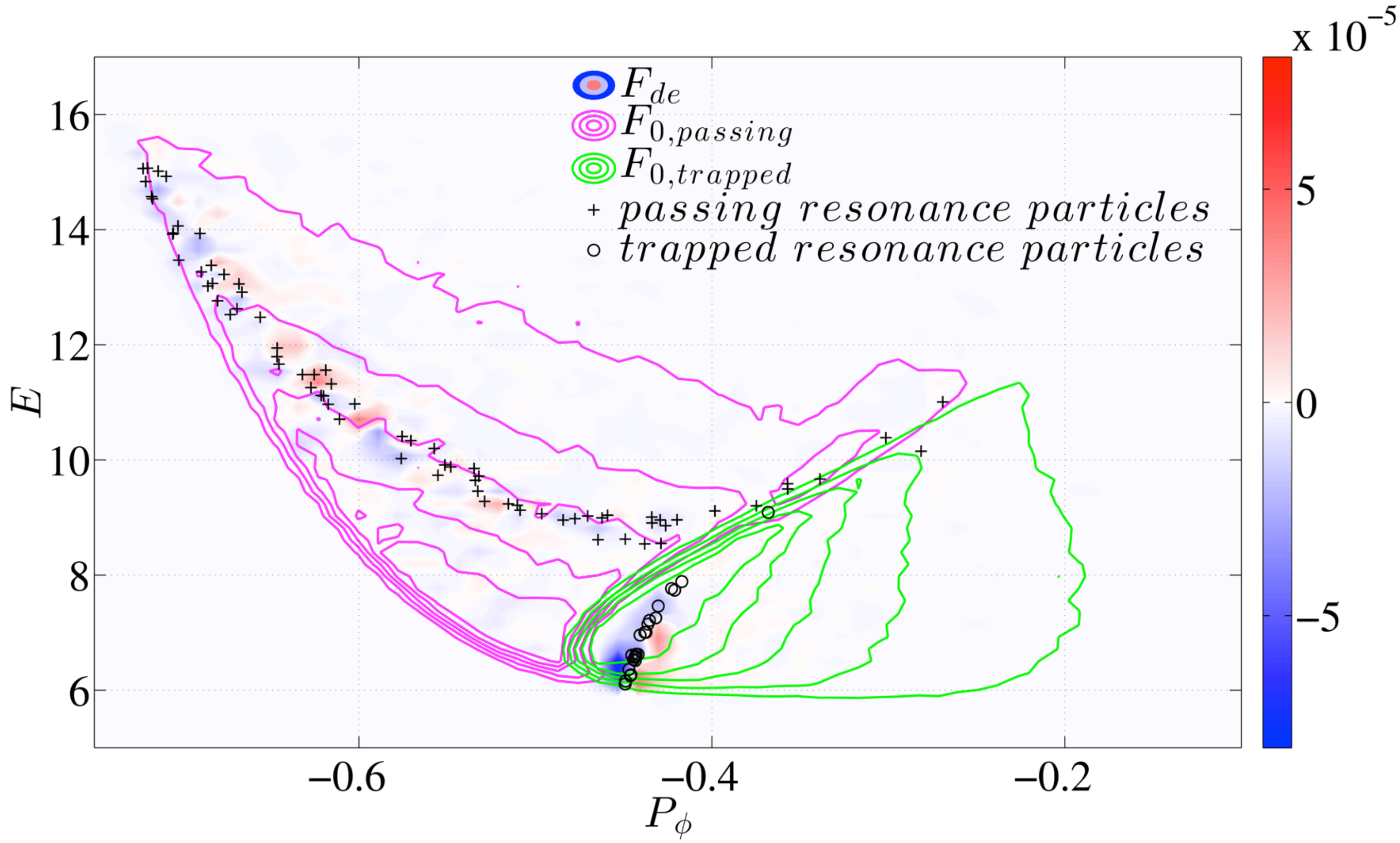


q_{min}=1.121

The mode structure is different at low q_{min} and high q_{min}. and rotation also change the mode structure at high q_{min}



Passing and trapped linear resonance location in phase space



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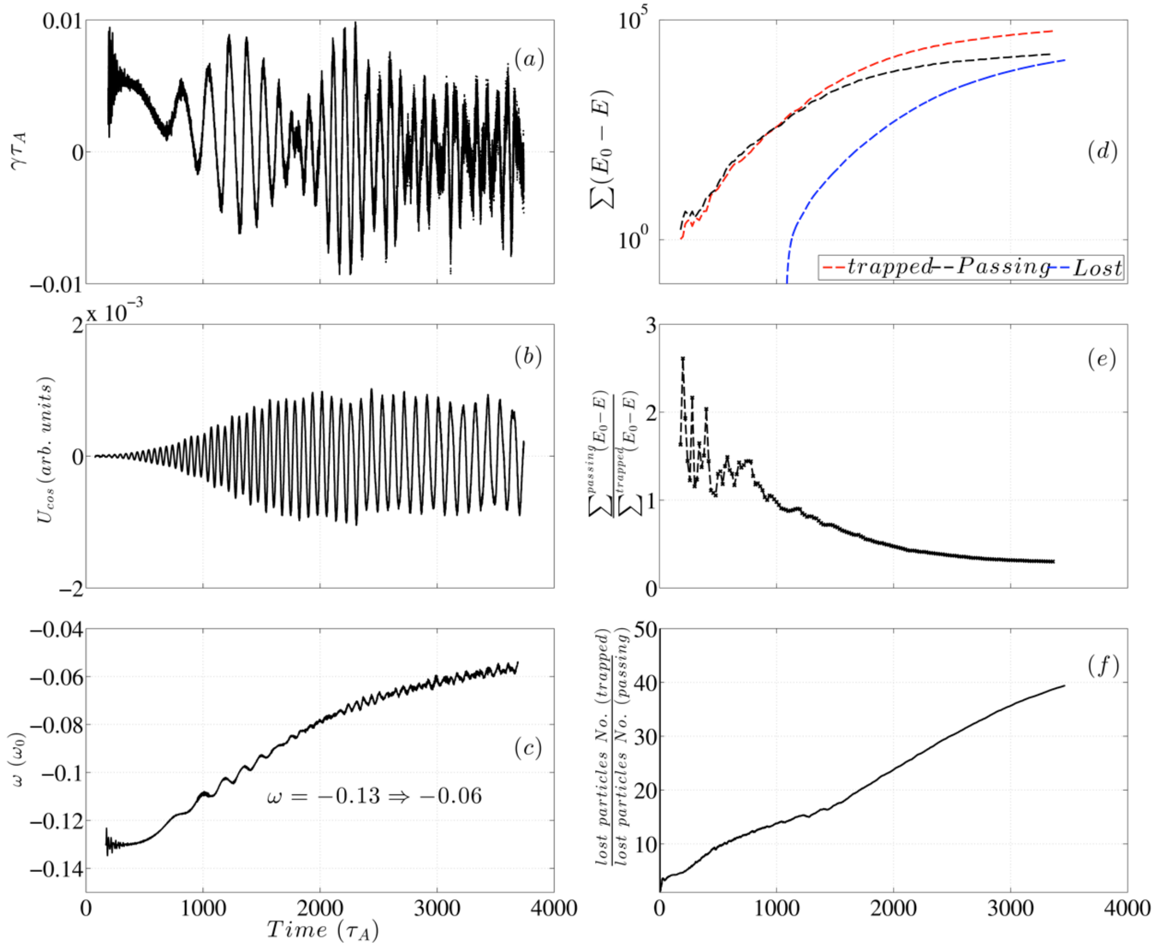
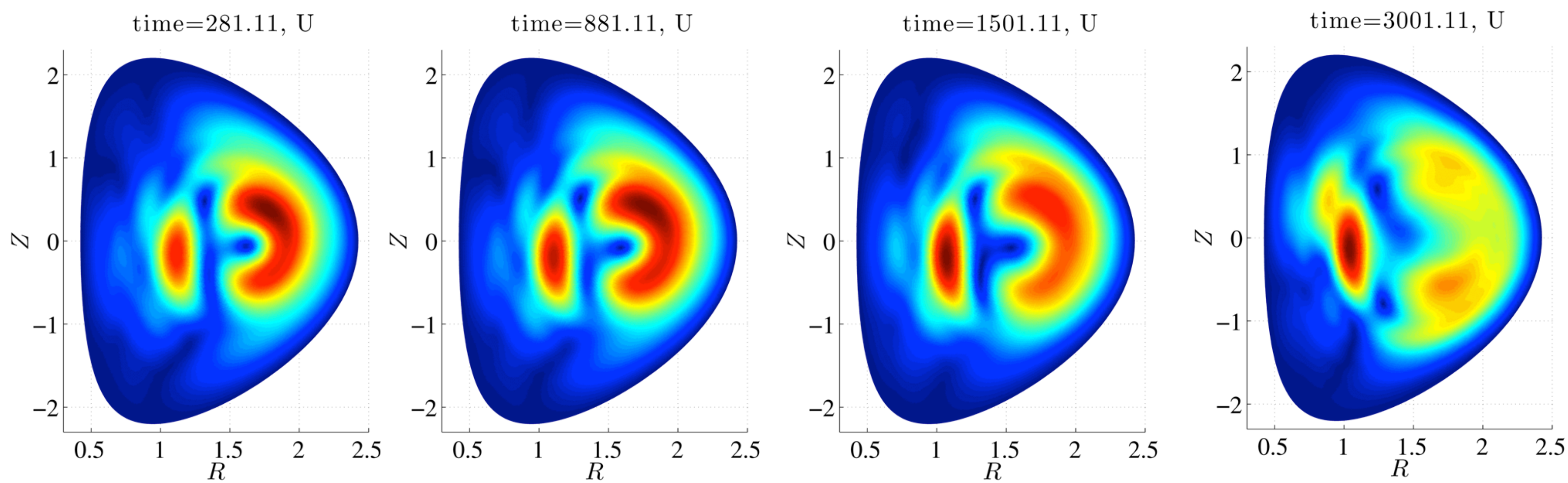
1. Nonlinear evolution:

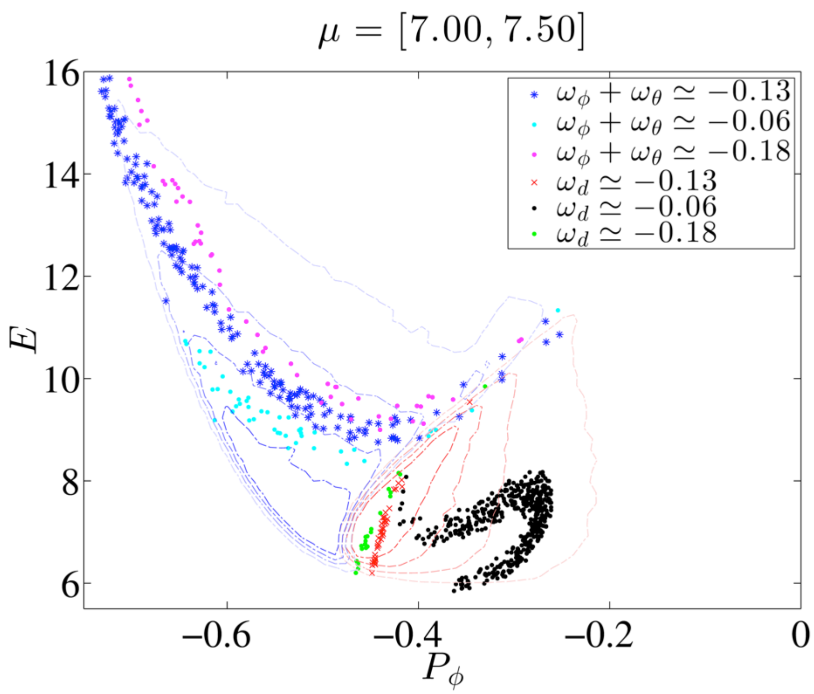
(1) mode saturates with strong downward frequency chirping,
(2) Both trapped and passing particles contribute to mode drive; trapped particle drive becomes more important nonlinearly;
(3) lost particles also play a role in driving the mode nonlinearly

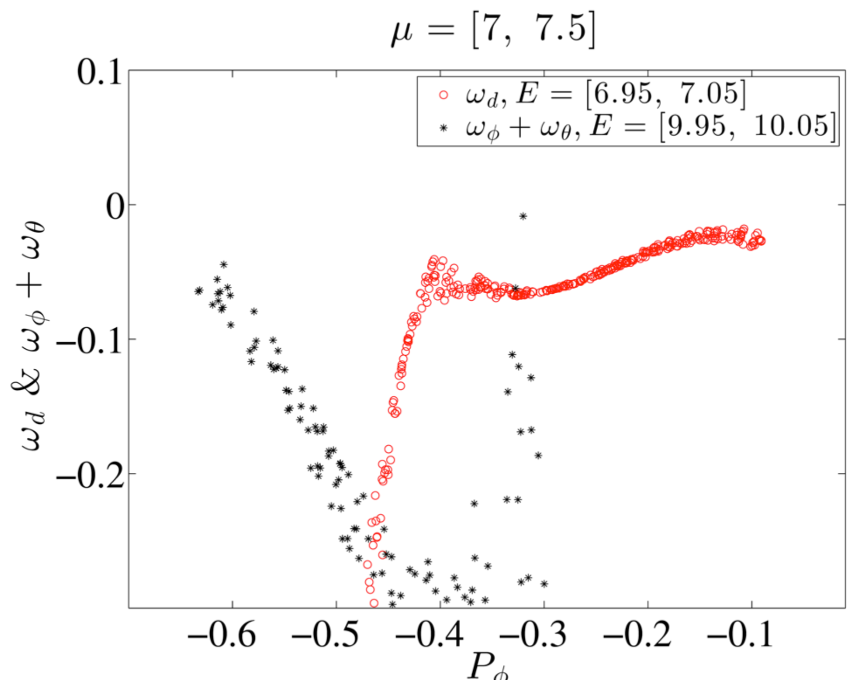


Mode structure broaden at low field side nonlinearly.



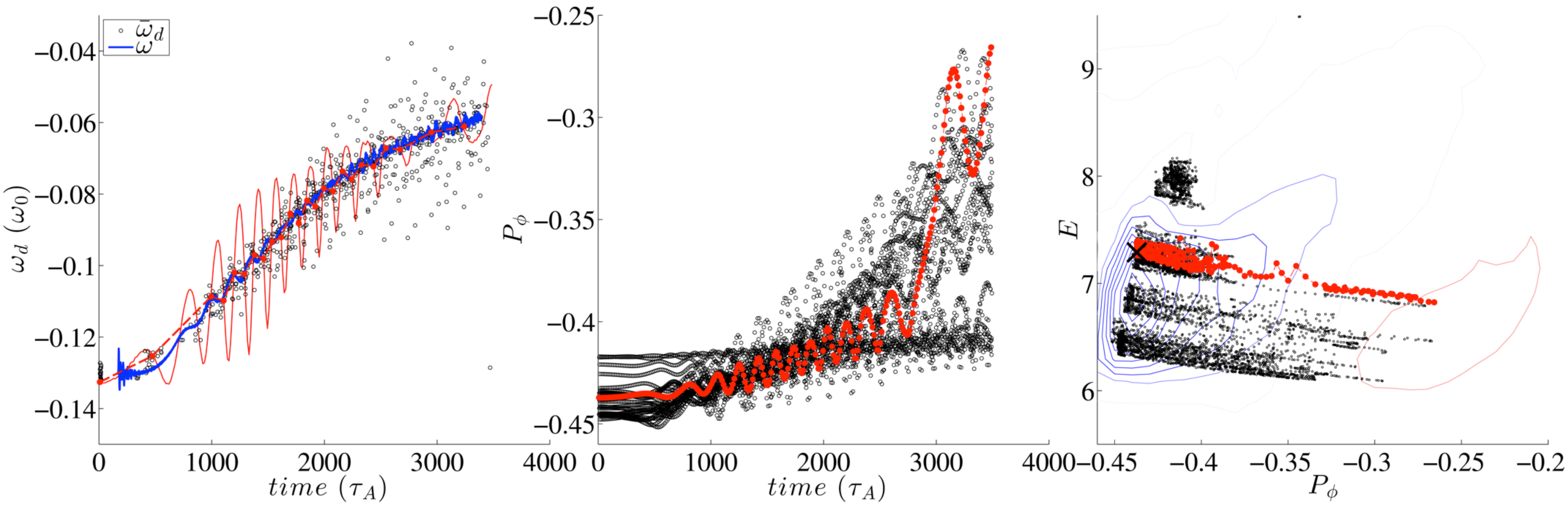
The key different between passing and trapped particles: resonant frequency decreases/increases as a function of P_Φ for trapped/passing particles



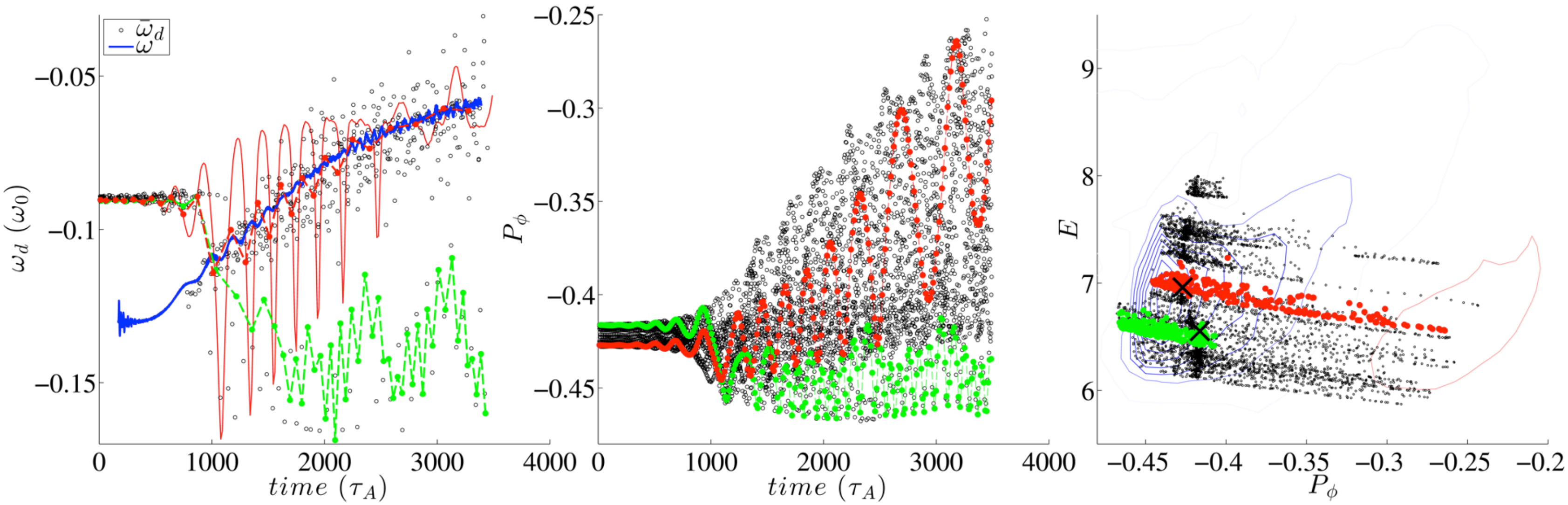


Unperturbed trapped and passing resonance particles and near resonance particles:

Nonlinear dynamic of trapped particles with initial frequency close to the linear mode frequency: almost all of those particles stay in resonance as frequency chirps down

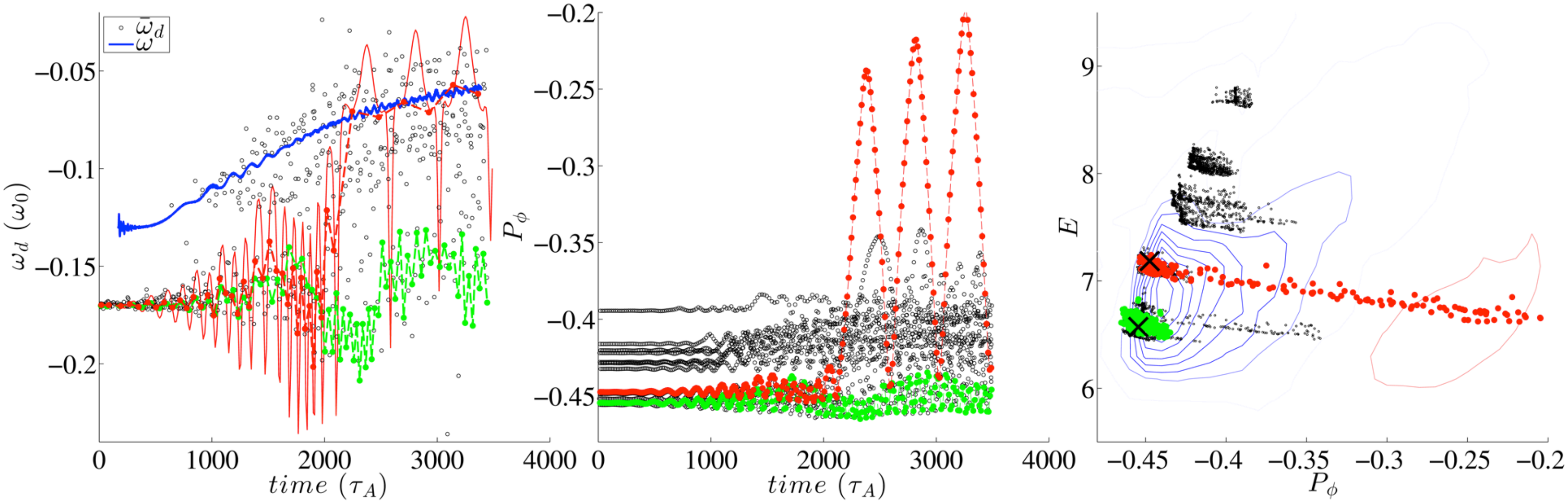


Nonlinear dynamic of trapped particles with initial frequency smaller than the linear mode frequency, most of those particles turn into resonant ones and stay in resonance as frequency chirps down



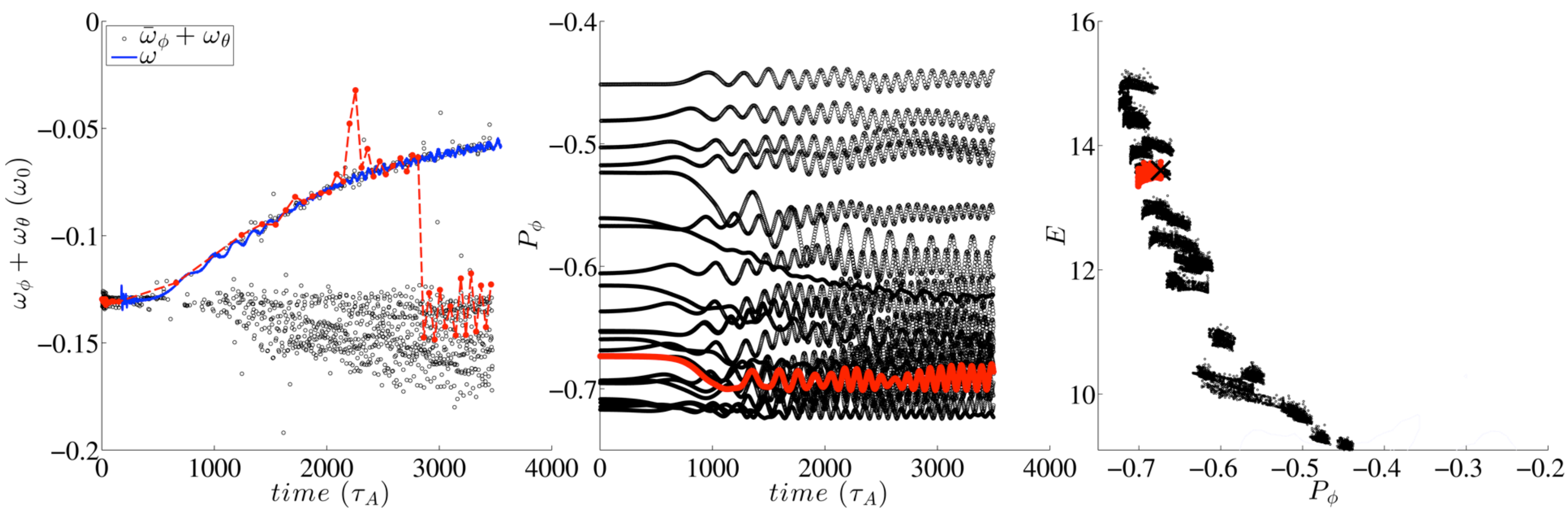
~90% particles turn into resonance

Nonlinear dynamic of trapped particles with initial frequency larger than the linear mode frequency: fraction of those particles turn into resonant ones and stay in resonance as frequency chirps down



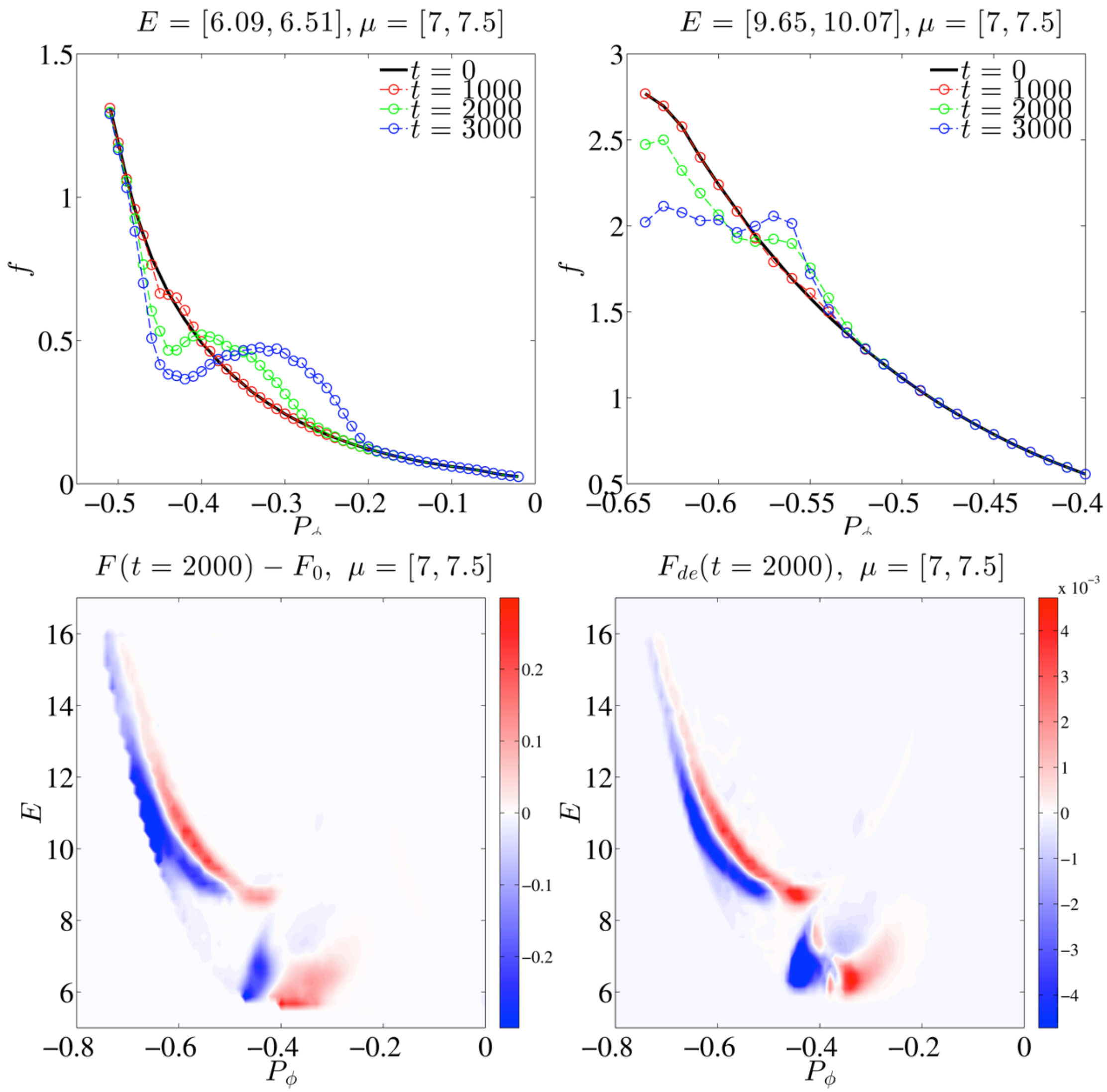
~36% particles turn into resonance

Nonlinear dynamic of passing particles with initial frequency close to the linear mode frequency:
only some of those particles stay in resonance; majority of those particles become non-resonant as frequency chirps down



~25% particles turn into resonance

The distribution function become flat around the resonant region, and as the mode frequency chirping down, trapped particles are transported from the core to the edge and flattening region becomes broader



Conclusions

- Rotation effect is destabilizing for fishbone at higher and lower q_{min} .
- Linearly, passing particles are also important to drive fishbone mode.
- The fishbone nonlinear chirping is due to the trapped resonant particles moving outward radially and keeping in resonance with the mode. Correspondingly mode structure is broadened at low field side.
- Due to the different resonant frequency profiles in phase space, majority of passing particles become non-resonant nonlinearly while trapped resonant particles stay in resonance as frequency chirps down.
- Nonlinearly, as the mode frequency chirping down, linearly non-resonant particles can turn into resonant ones. This provides additional drive to sustain the mode.
- The phase space island width is large in P_Φ leading to a significant flattening region in the distribution function. This is different from the hole/clump structure predicted by Berk-Breizman theory.