Studies of energetic particle-driven modes and energetic particle transport via kinetic-MHD hybrid simulation

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**SicDAC Center for Nonlinear Simulation of Energetic Particles in Burning Plasmas (CSEP)*
***Max Planck/Princeton Research Center for Plasma Physics (MPPC)*

PPPL Theory Department Research Seminar, Feb. 14, 2014

Outline

1. Motivation and M3D-K hybrid model

2. Marker removal method for efficient simulations of EP instabilities (W.J. Deng, G.Y. Fu, CPC 2013)
3. Simulations of beam-driven TAE in NSTX (D.Y. Liu et al, paper being written)
4. Linear Stability and Nonlinear Dynamics of Fishbone in NSTX (F. Wang, G.Y. Fu, J. Breslau, J.Y. Liu, PoP 2013)
5. M3D-K Simulations of Sawteeth and Energetic Particle Transport in Tokamak Plasmas (W. Shen et al., paper being written)

6. Future work:
   Simulation of multiple beam-driven TAEs in NSTX
   Simulations of fishbone in DIII-D and HL-2A
   Effects of runaway electron on MHD modes in JET
   Simulation of alpha-driven TAEs in ITER
   Interaction of EGAM and plasma micro-turbulence

Motivation

- Energetic particle (EP)-driven instabilities can induce significant alpha particle 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 Particle/MHD Hybrid Model

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

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

$$\frac{dP_{th}}{dt} = -\gamma P_{th} \nabla \cdot \mathrm{v}$$

P_h is calculated using gyrokinetic equation via PIC

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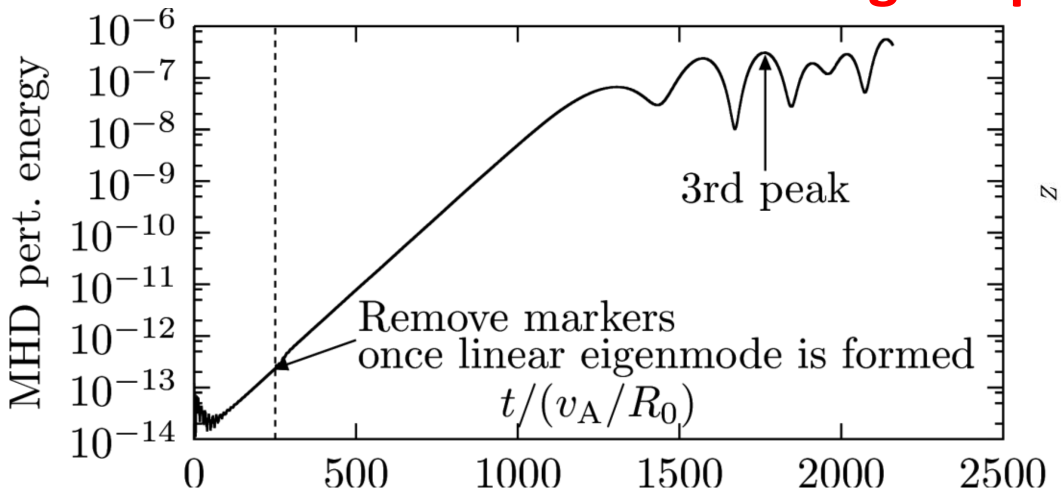
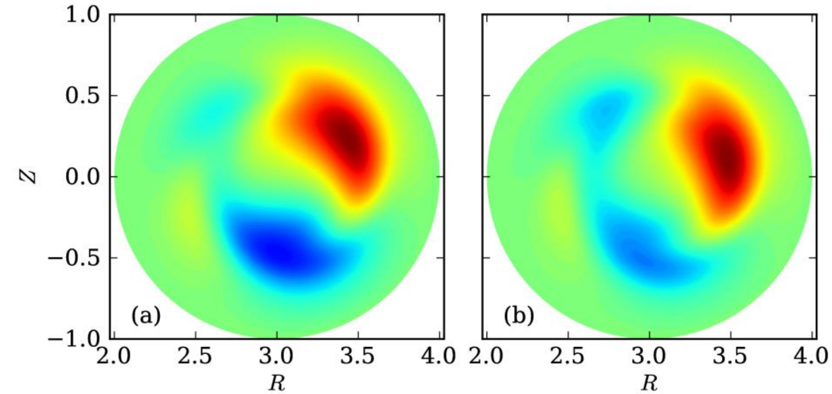
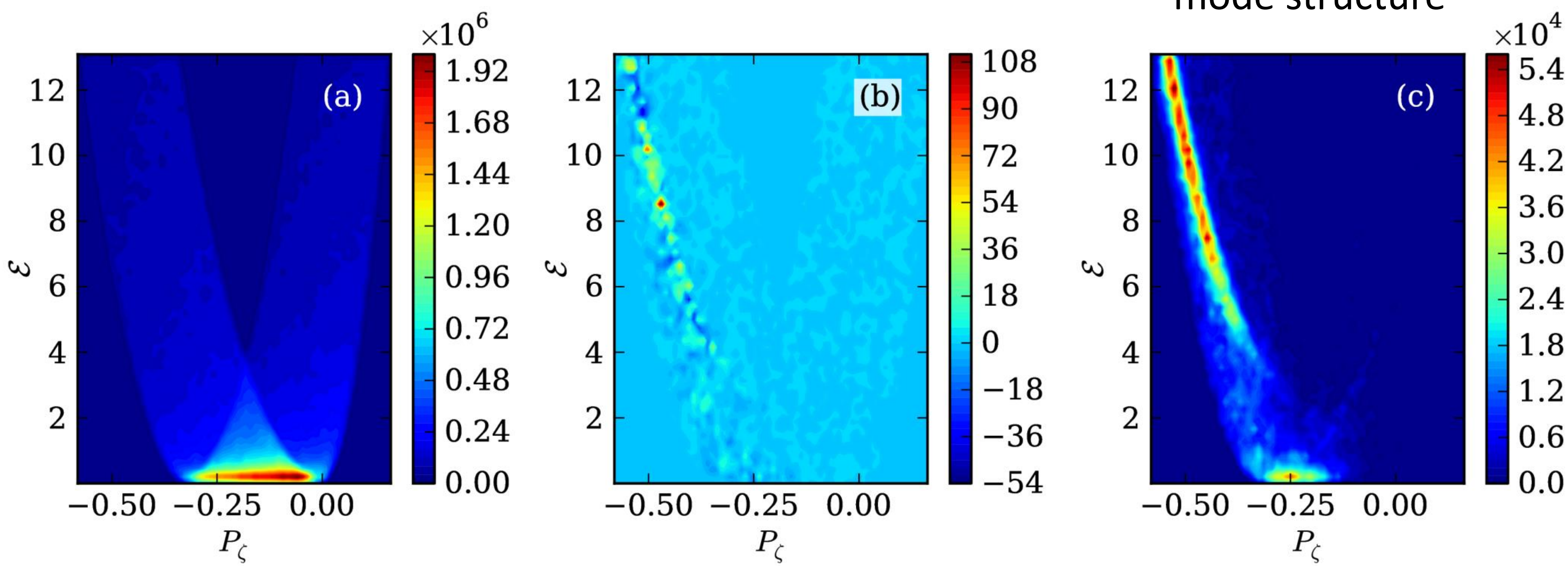
Marker removal method developed and implemented in M3D-K for efficient simulations of energetic particle-driven instabilities





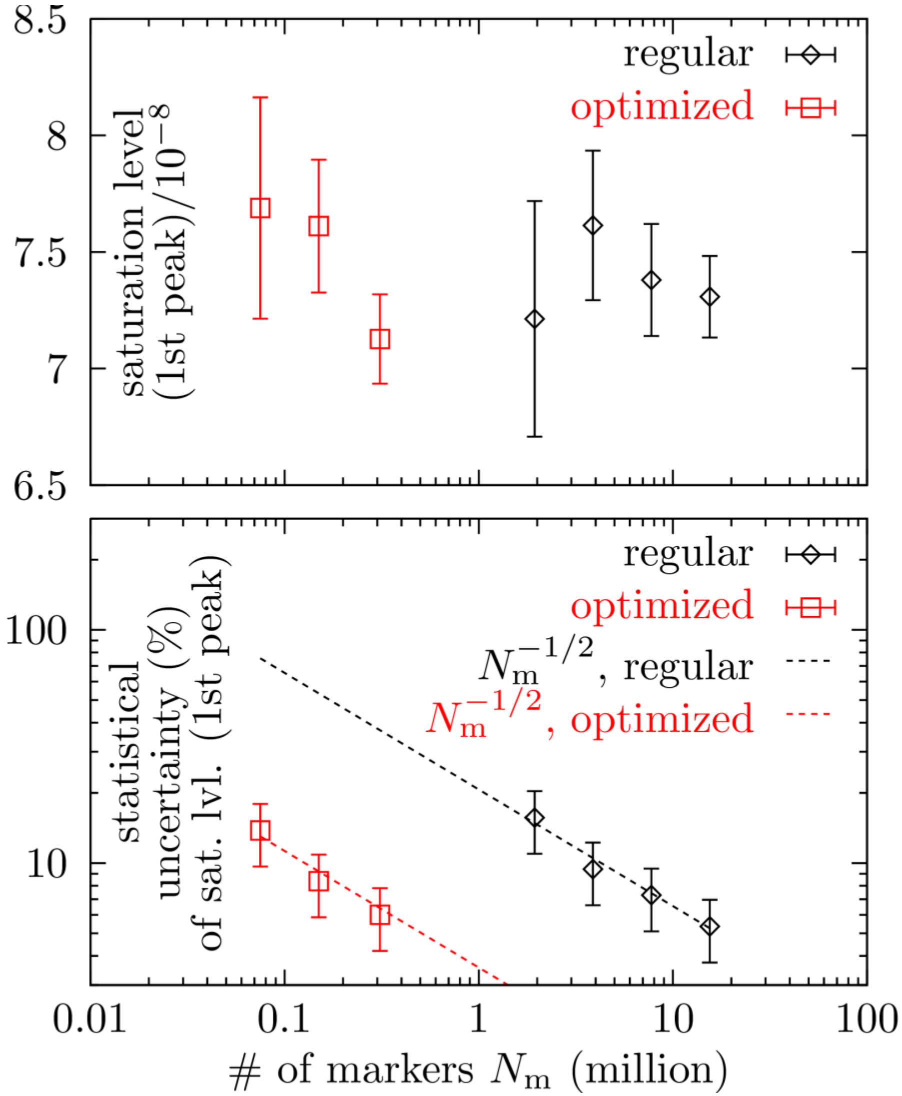
$n = 1$ TAE linear and nonlinear mode structure



Pre-removal marker distribution and δf, and post-removal marker distribution, in the $\mu = 0$ slice of the z_n-integrated phase space

The marker removal method saves simulation particles by a factor of 34 for the TAE saturation level

W.J. Deng and G.Y. Fu, CPC 2013



- PIC simulation is essentially a Monte Carlo simulation. Numerical error is mainly statistical rather than systematic.
- Our marker removal technique:
  - does not introduce apparent systematic error;
  - saves marker by a factor of 34 for TAE nonlinear saturation level while retaining the same statistical uncertainty.

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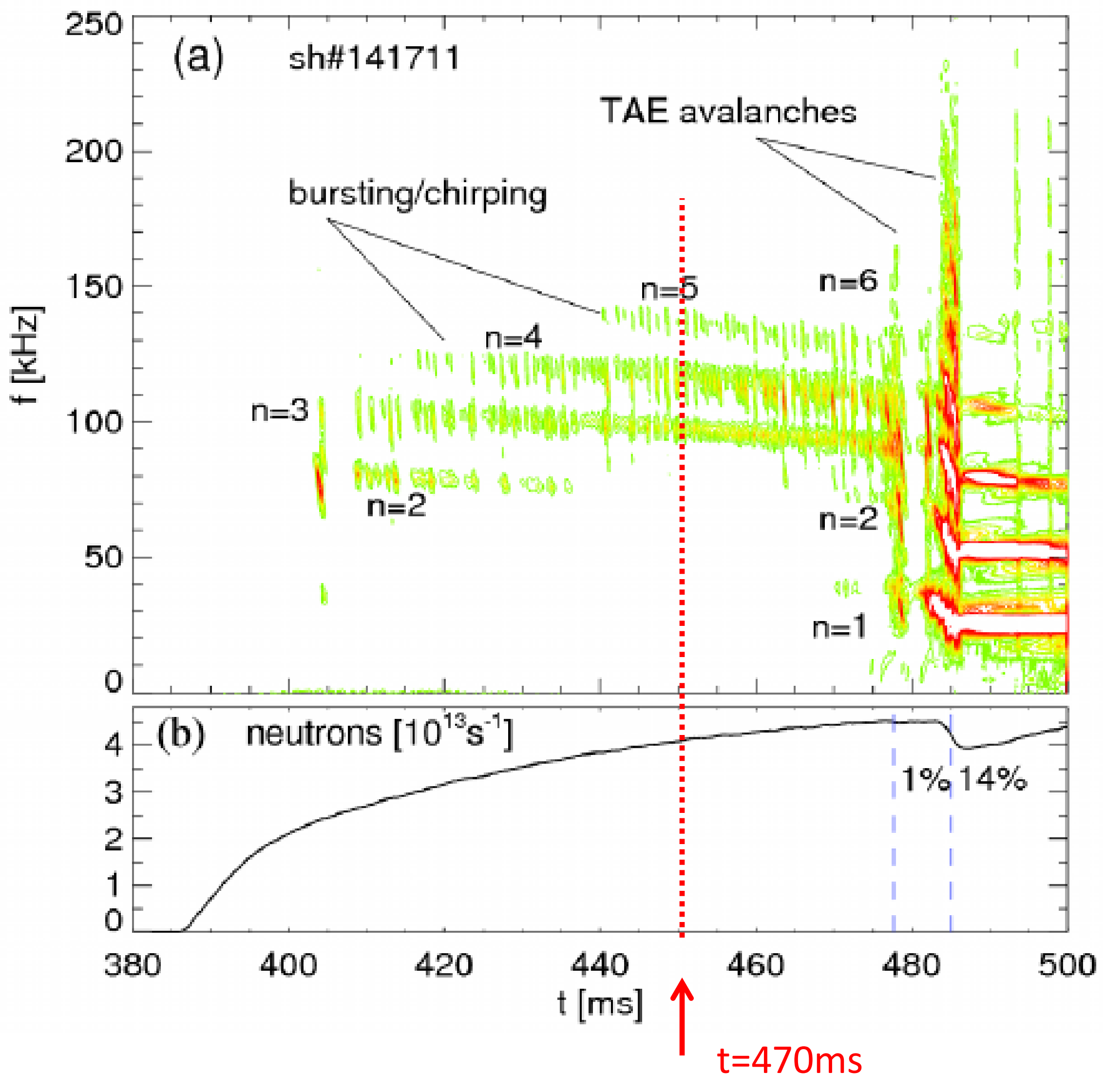
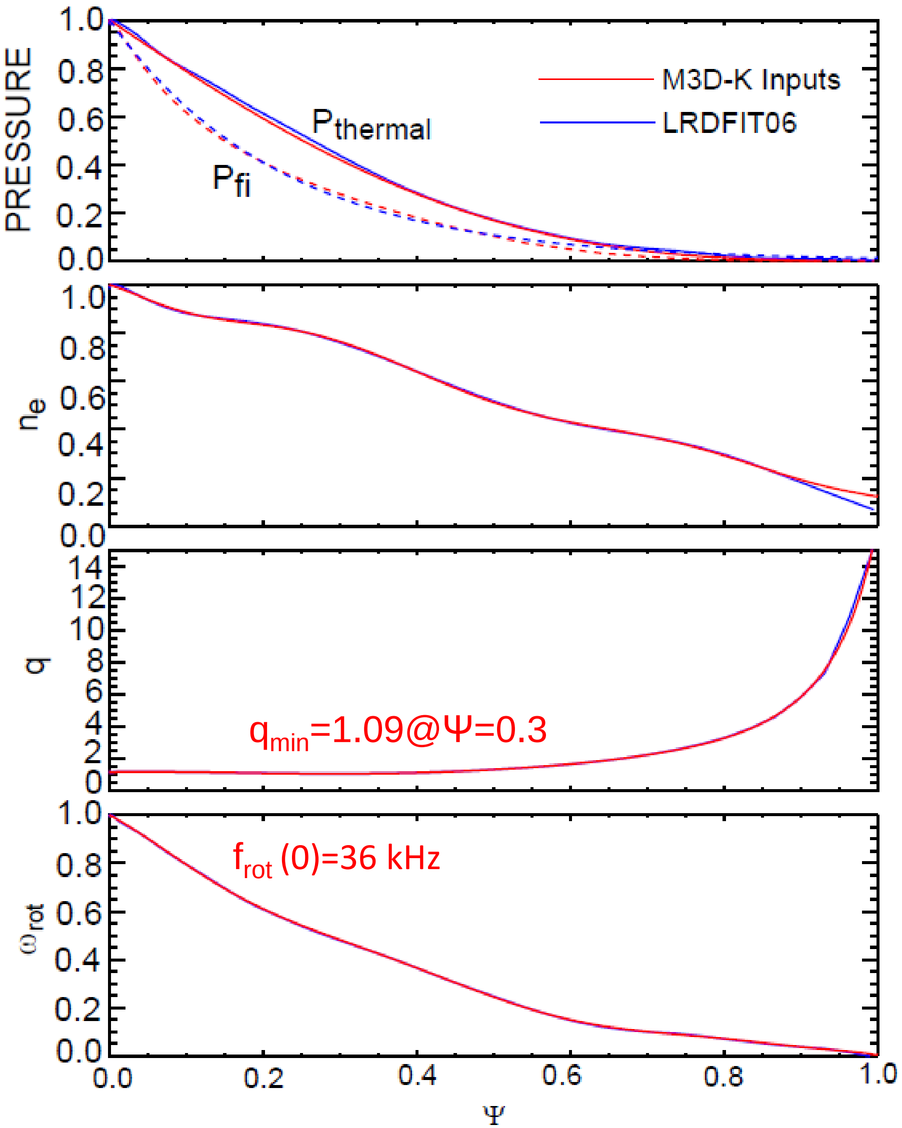
Beam-driven Alfven modes are routinely observed in NSTX.
M3D-K is used to simulate beam-driven TAEs for code validation.



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

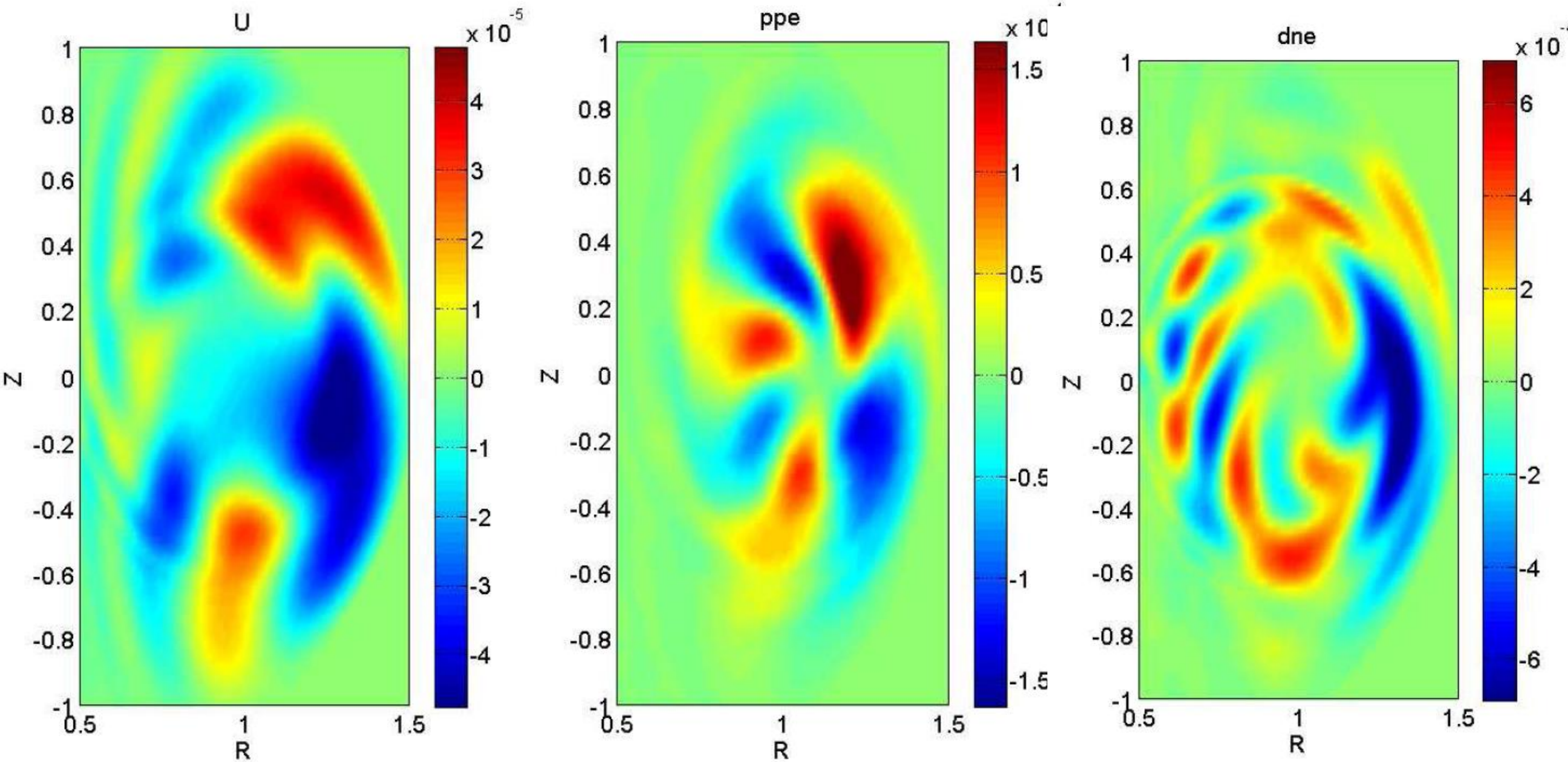
- ➢ Self-consistent equilibrium with plasma rotation and fast ion pressure
  - $\beta_{tot}(0)$=18.4%, $\beta_{fi}(0)$=6.5%
  - analytic or numerical fast ion distribution

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

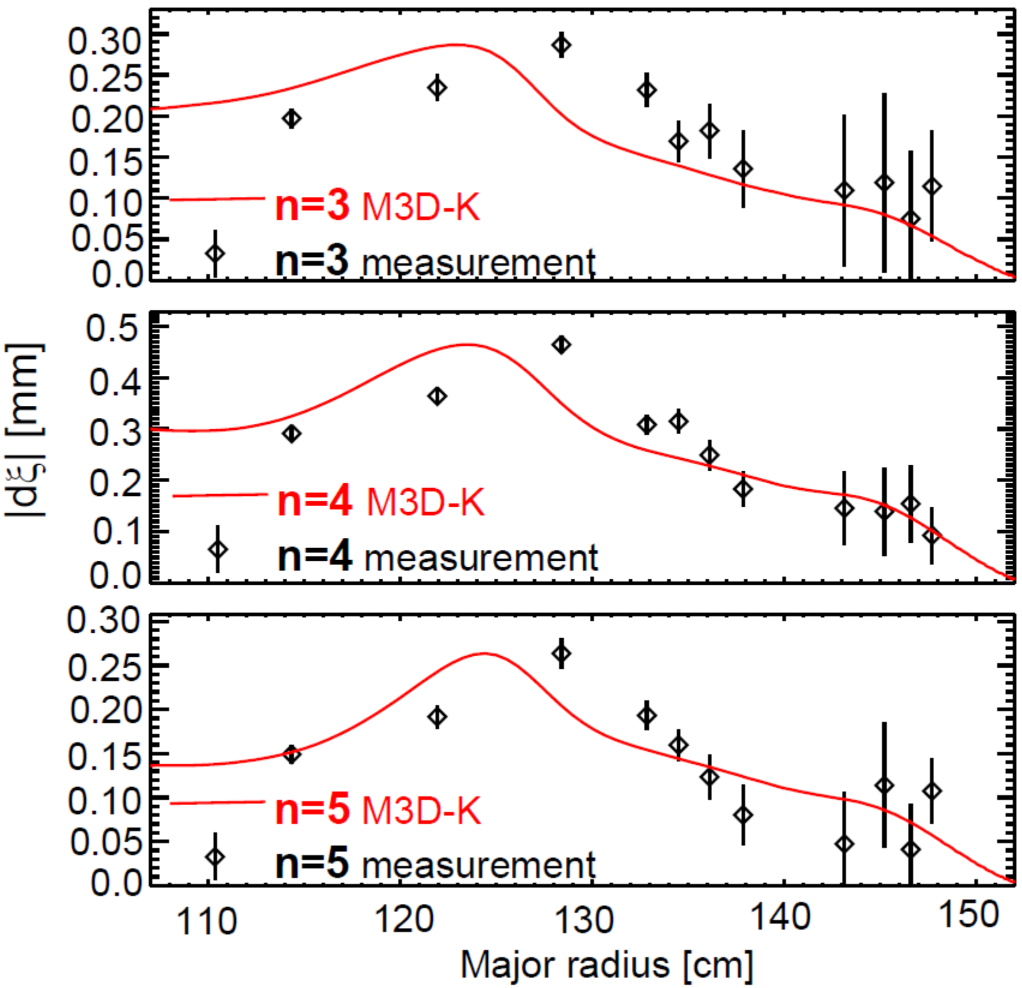
v_{fi} / v_{alfven}=2.5, P_{NBI}= 2MW

n=3 Simulation Exhibits TAE-like Global Feature

U $\quad\quad$ $P_{//}$ $\quad\quad$ 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

	n=3	n=4	n=5
f_{exp} (kHz)	**100**	**120**	**140**
f_{M3D-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

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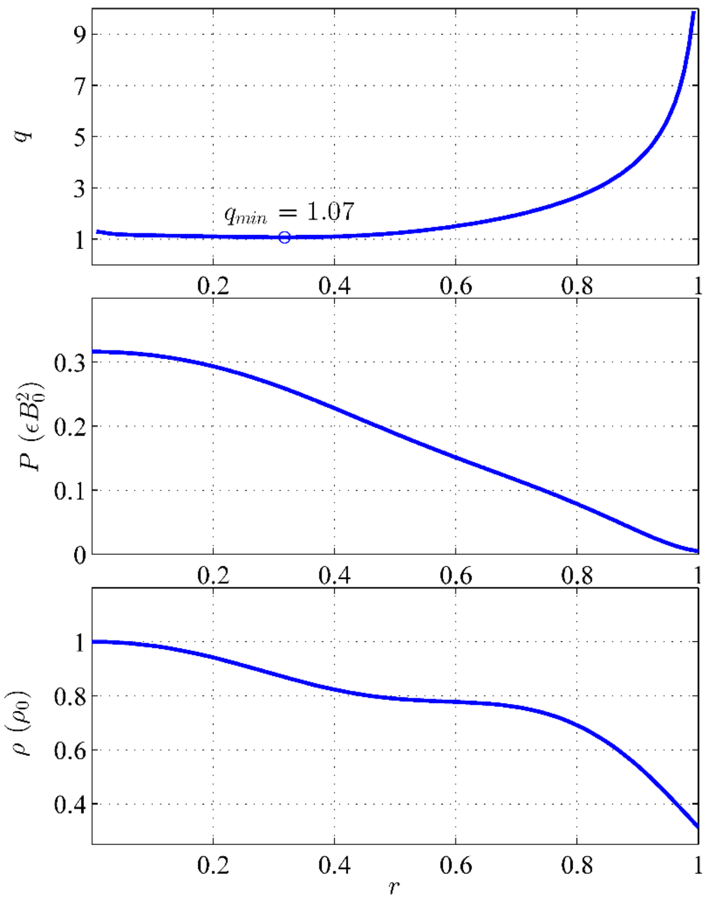
Linear Stability and Nonlinear Dynamics of Fishbone in NSTX

F. Wang, G.Y. Fu, J. Breslau, J.Y. Liu

- 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

Equilibrium profile and parameters

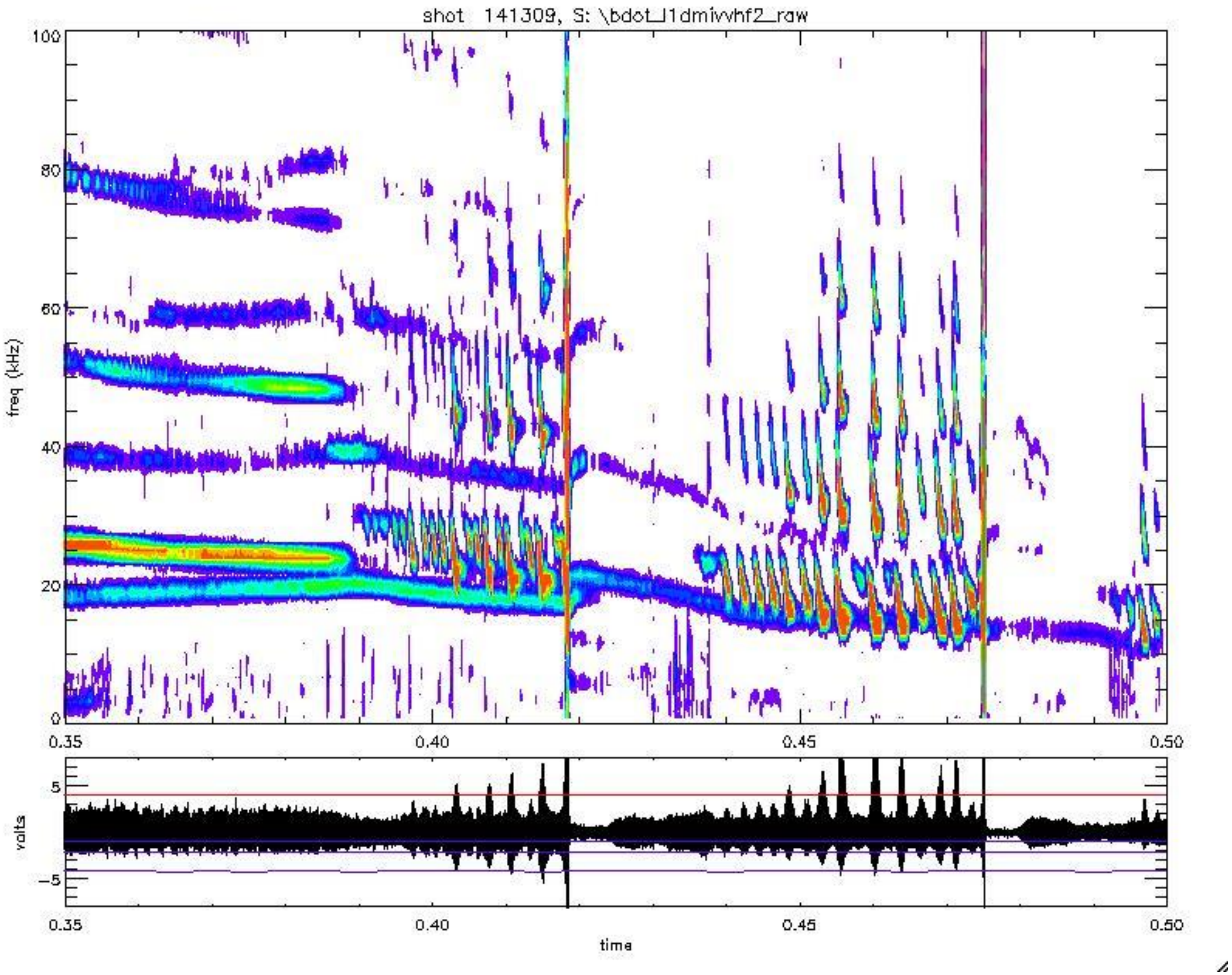


$\beta \sim 0.3$
$q_{\min} \sim 1.03 \rightarrow 1.2$
$R_0 = 0.858m$
$a = 0.602m$
$B_0 = 0.44T$
$n_0 = 9.3 \times 10^{19} m^{-3}$

$\eta(T) = \eta_0 (T/T_0)^{-3/2}$
$\eta_0 = 5 \times 10^{-6}$
$\mu = 1 \times 10^{-4}$
$\chi_\perp = 5 \times 10^{-5}$

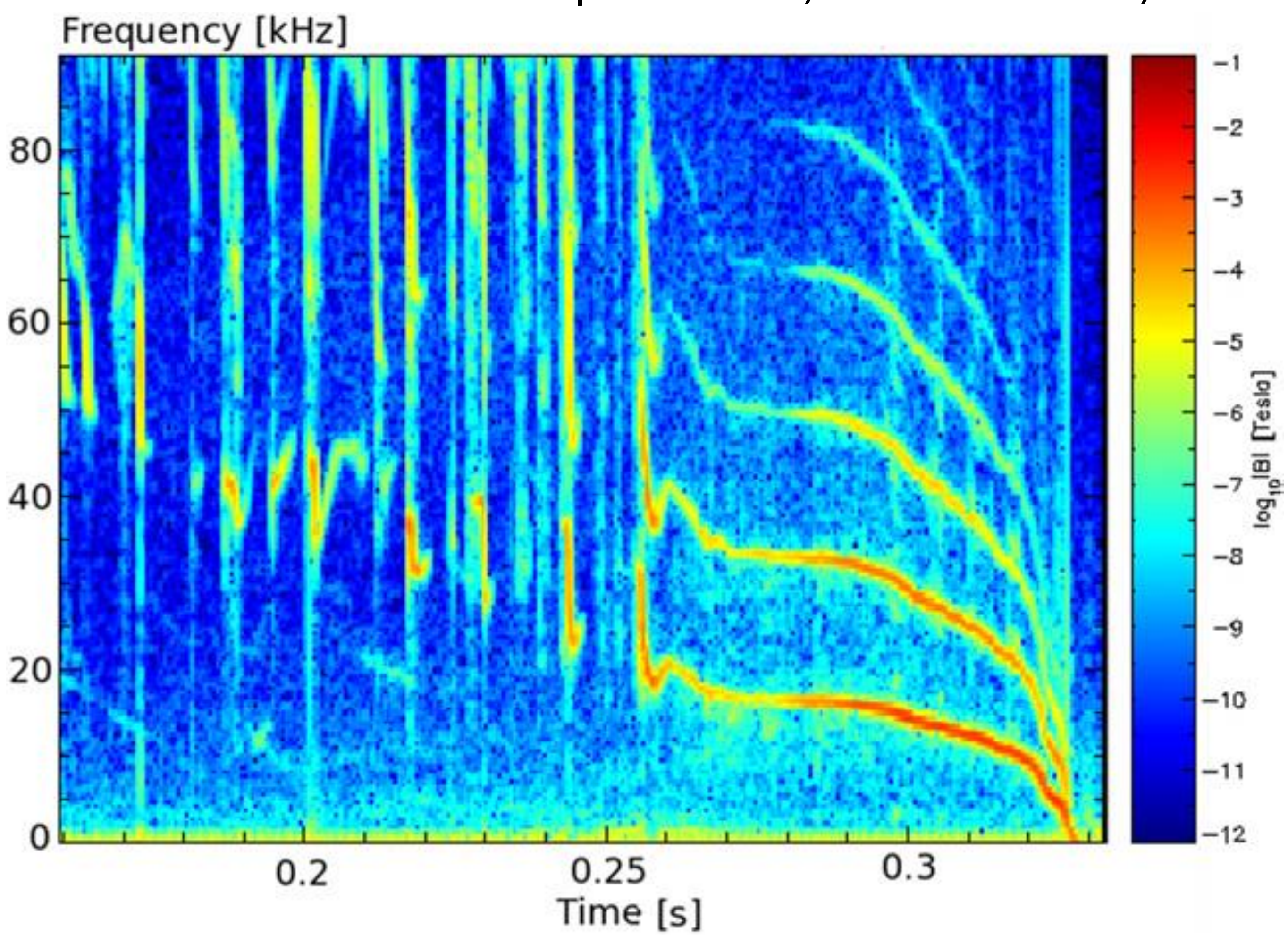
NSTX #124379 at t=0.635s

Beam-driven fishbones are observed in NSTX

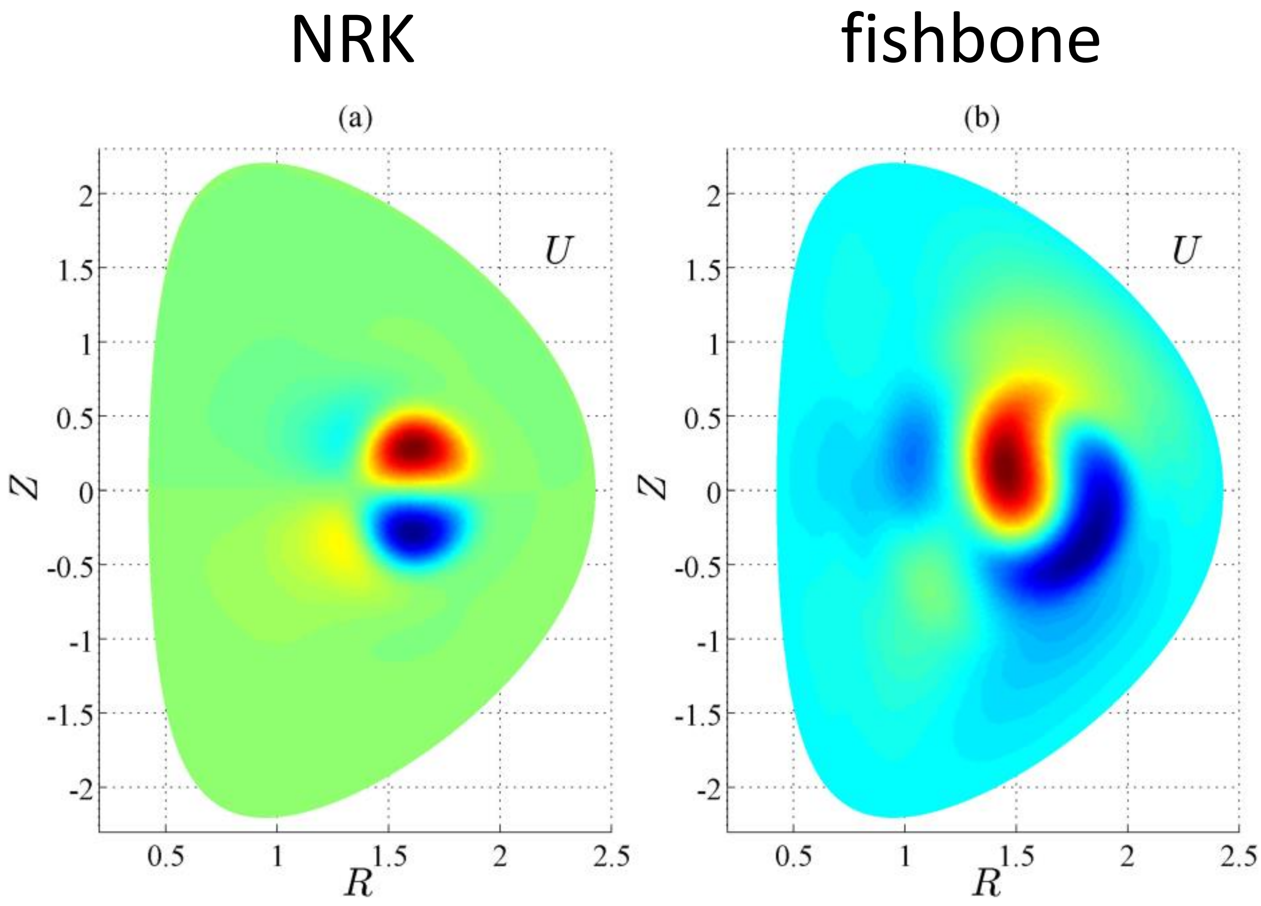


Fishbone and NRK (LLM) were observed in STs and tokamaks

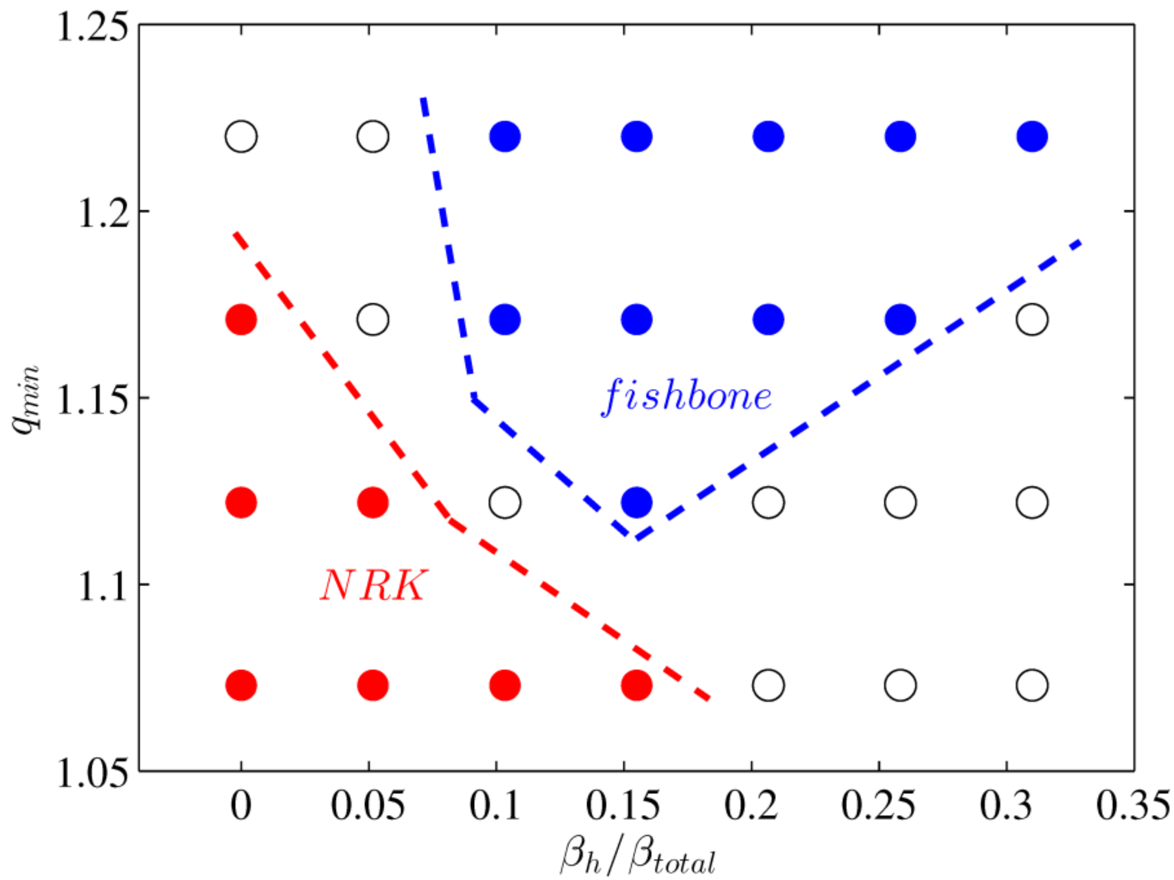
I.T. Chapman et al., Nucl. Fusion 50, 045007 (2010)



The fishbone mode structure shows twisting feature

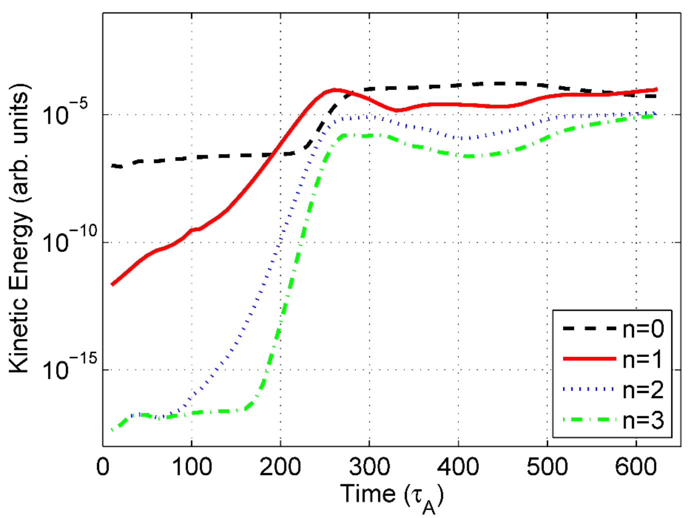


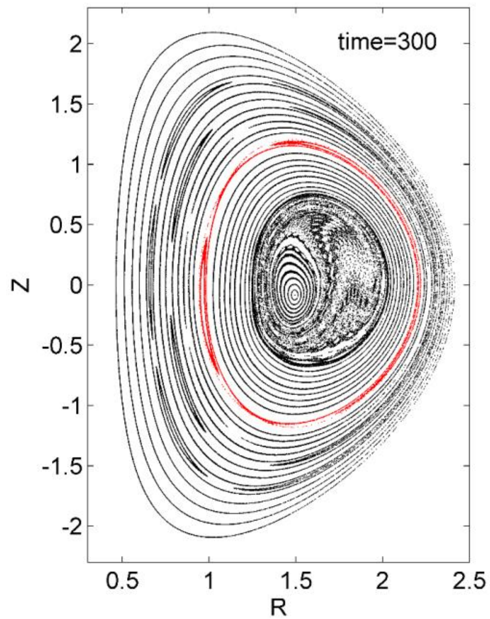
Stability diagram: stabilization of ideal kink and excitation of fishbone at higher q_min



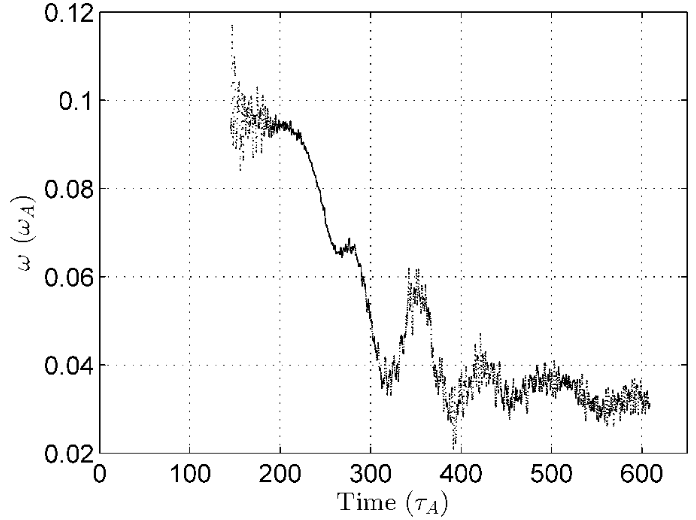
At fixed P_total at axis

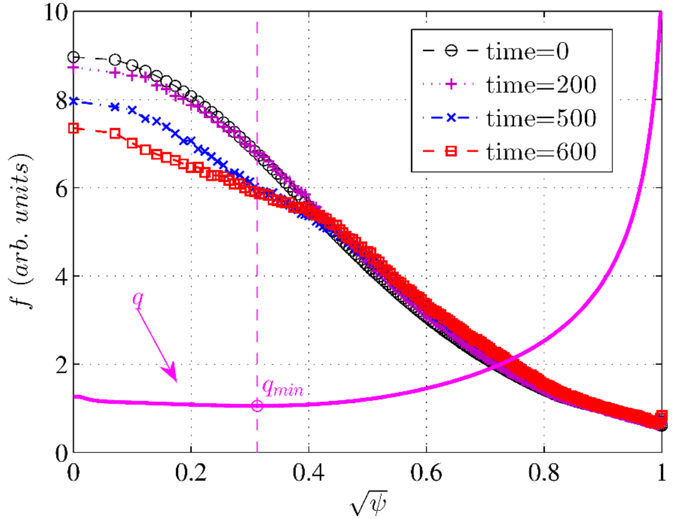
Fishbone nonlinear evolution





Nonlinearly, the fishbone shows strong frequency chirping, and induces 2/1 island, which could trigger NTM.
It induces strong beam ion profile flattening in the core.





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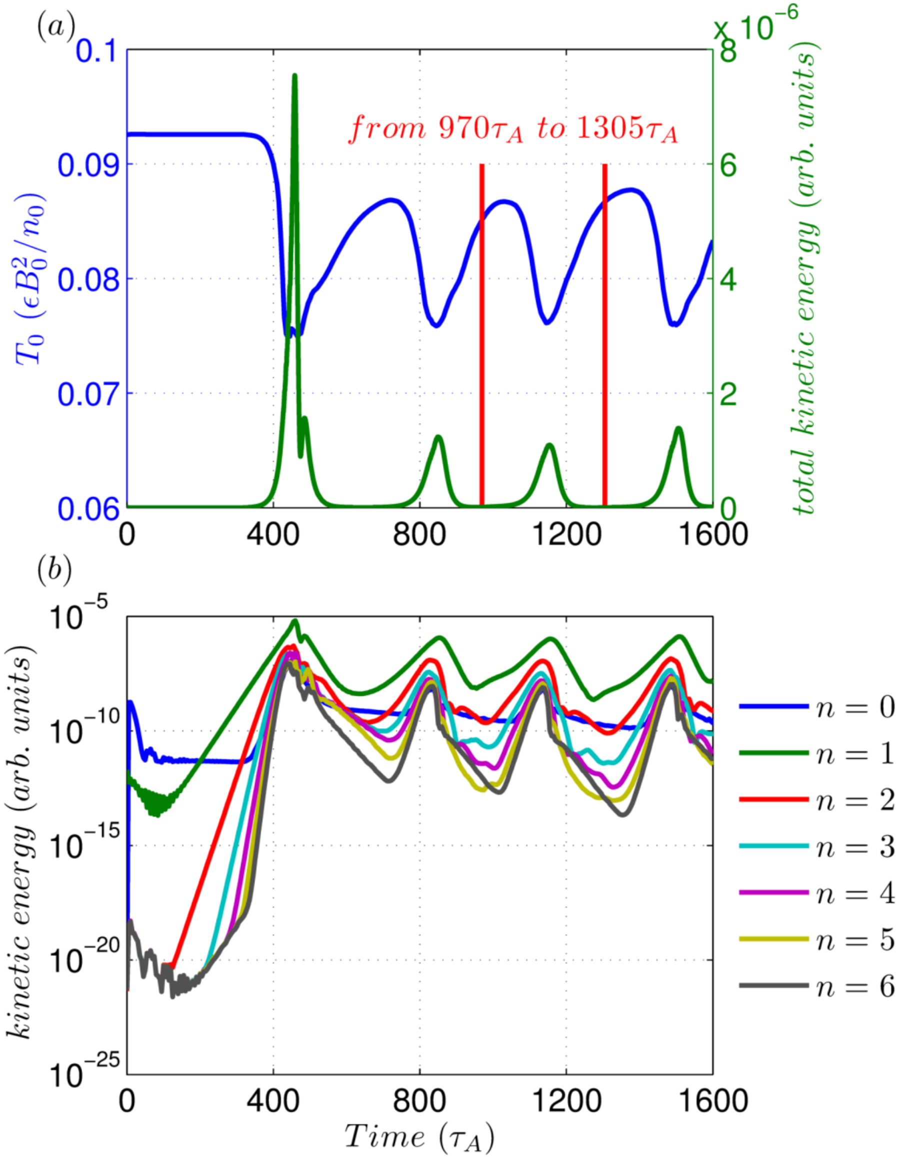
M3D-K Simulations of Sawteeth and Energetic Particle Transport in Tokamak Plasmas

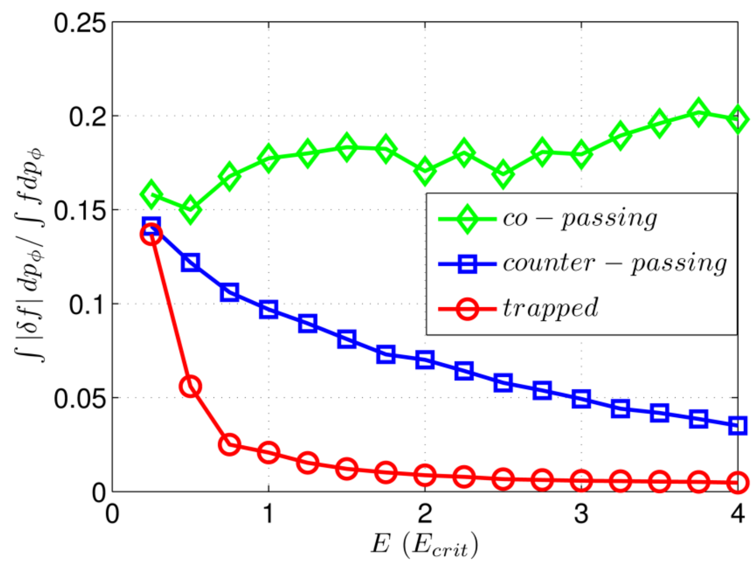
W. Shen, G.Y. Fu, Z.M. Sheng



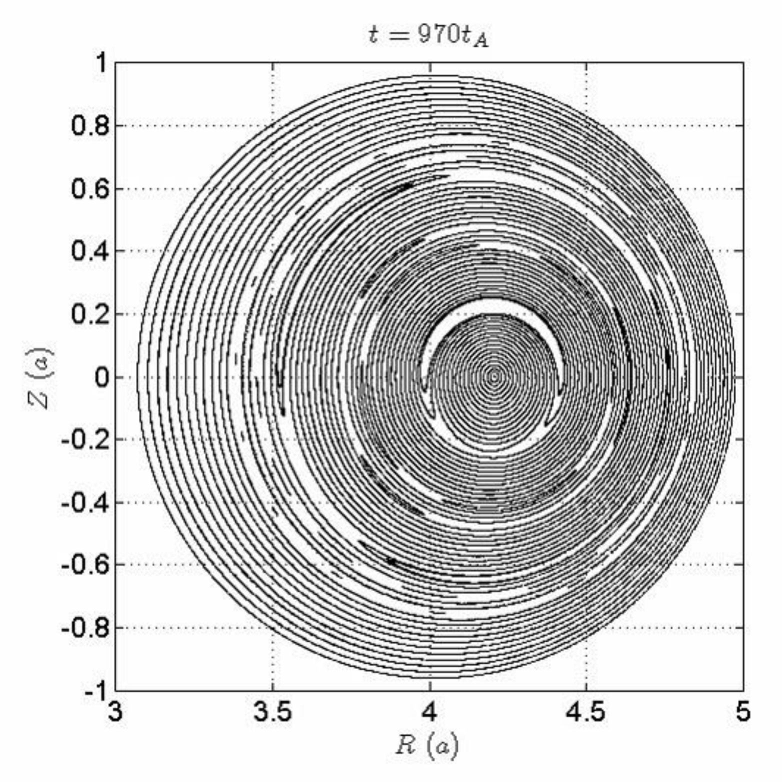
M3D-K code is used to simulate energetic particle transport during a sawtooth. The background sawteeth is self-consistently evolved using resistive MHD model.

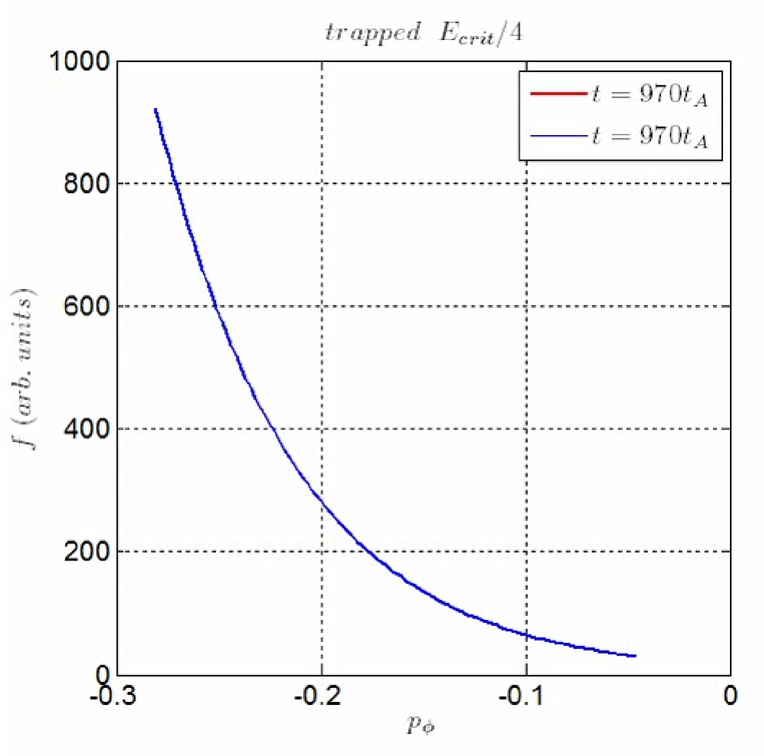
E_{crit} corresponds to: v_h/v_A=0.7275, ρ_h/a =0.04656

$\Lambda=\mu B_0/E$ passing particles with Λ=0; trapped particles with Λ=1.0



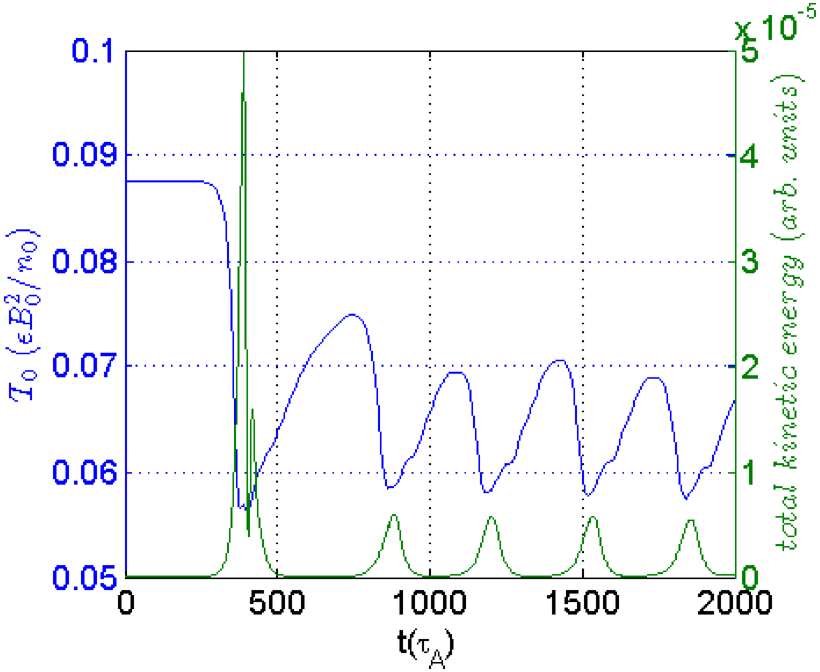
Sawtooth movie: Poincare plot and fast trapped ion distribution





Simulation of sawteeh with energetic particle effects

(a)



(b)

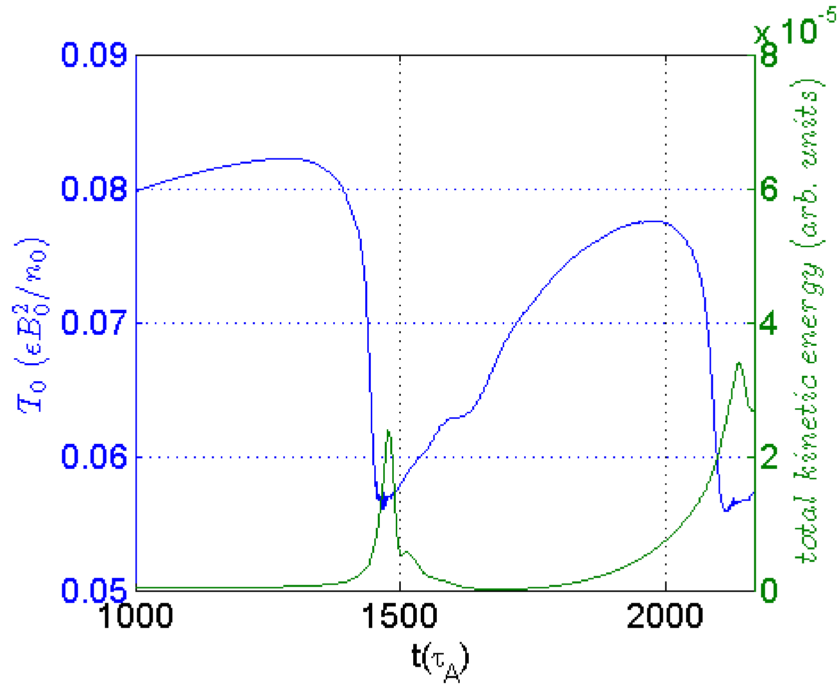


Fig. (a) shows the results using MHD model without EP, $P_{thermal} \propto [0.75(1-\psi)+0.25 \exp(-\psi/0.25)]$, $\beta_0 \sim 4.21\%$, sawtooth period is around $327\tau_A$.

Fig. (b) shows the results with EP loading around $660\tau_A$, $P_{hot} \propto \exp(-\psi/0.25)$, $\beta_h/\beta_{total} \sim 0.2$, sawtooth period is around $655\tau_A$.

Summary :M3D-K Simulations of Sawteeth and Energetic Particle Transport: Summary

- MHD simulations show repeated sawtooth cycles due to a resistive (1,1) internal kink mode for a model tokamak equilibrium.
- Test particle simulations are carried out to study the energetic particle transport due to a sawtooth crash.
- For trapped particles, the redistribution occurs for particle energy below a critical value in agreement with previous theory.
- For co-passing particles, the redistribution is strong with little dependence on particle energy. In contrast, the redistribution level of counter-passing particles decreases as particle energy becomes large.

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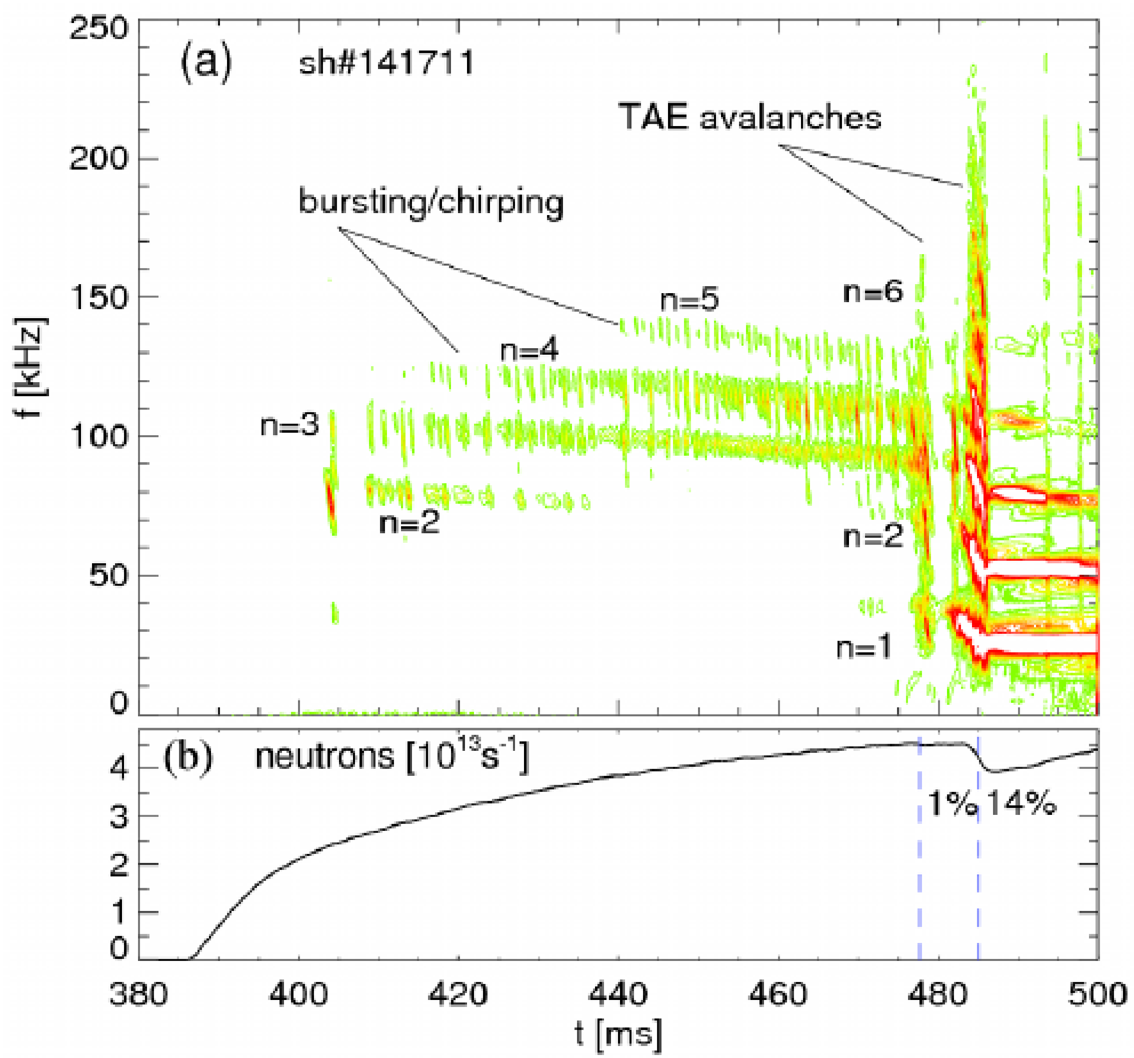
Future work: Simulation of multiple beam-driven Alfven modes in NSTX



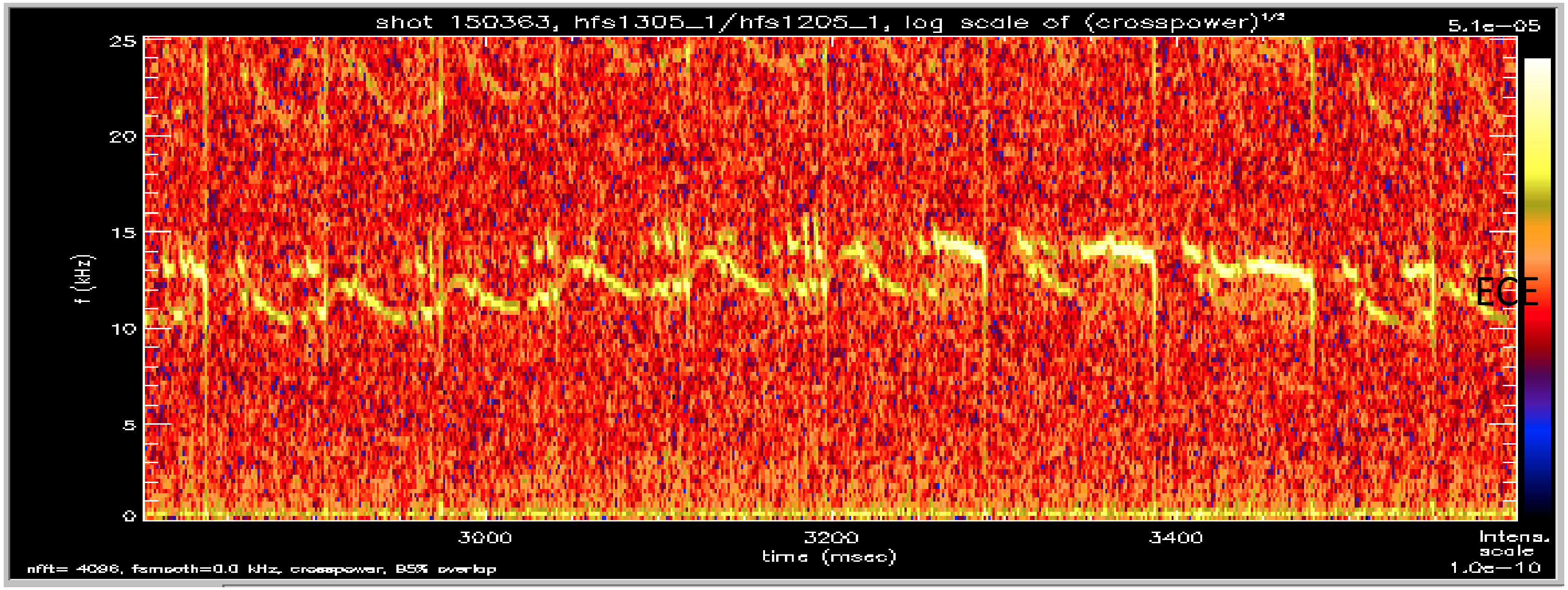
Future work: simulation of fishbone in DIII-D

W. Shen, G.Y. Fu, B. Tobias, M. Van Zeeland

Fishbone and saturated kink are observed between sawteeth crashes in DIII-D

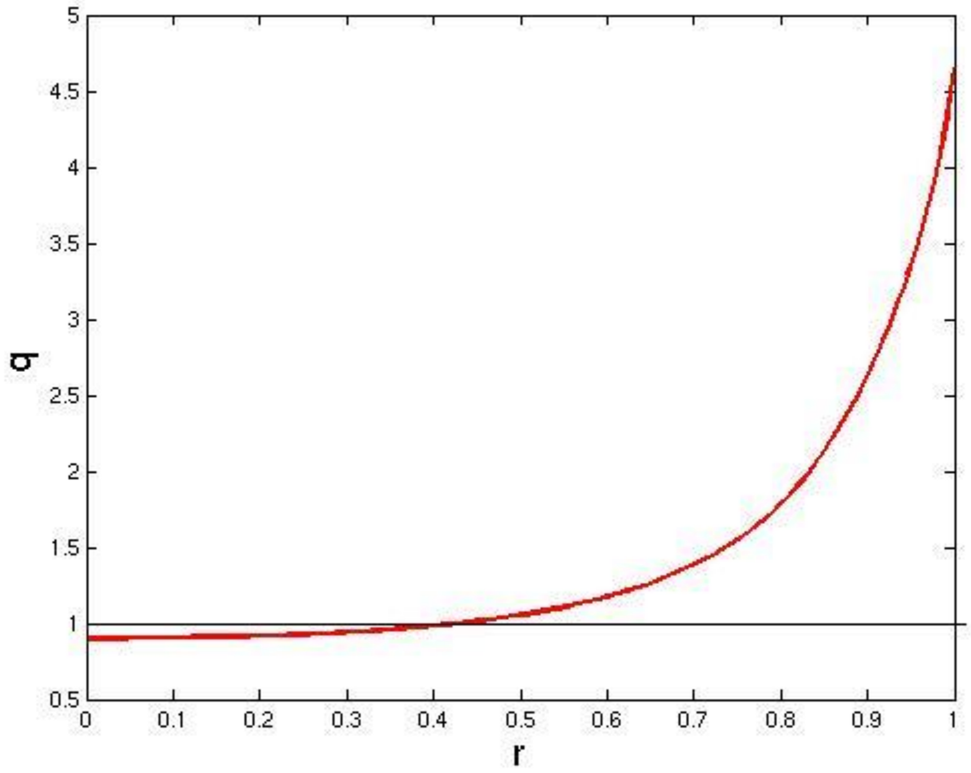
B. Tobias

DIII-D # a150363



Equilibrium profile and parameters

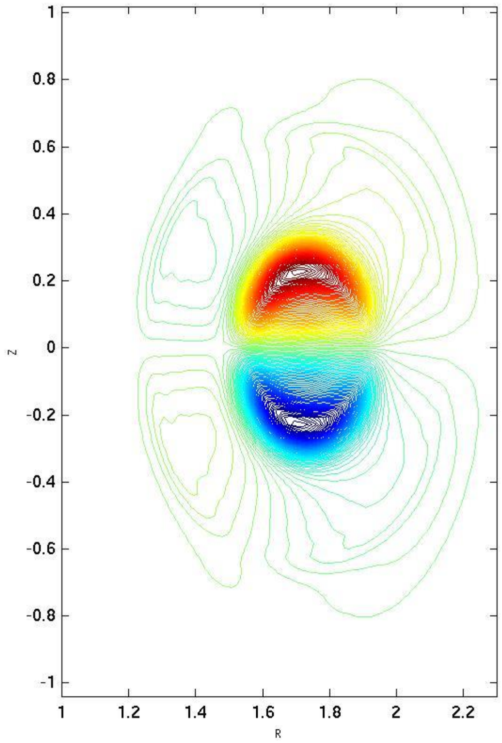
DIII-D # a150363_ t=3.11s



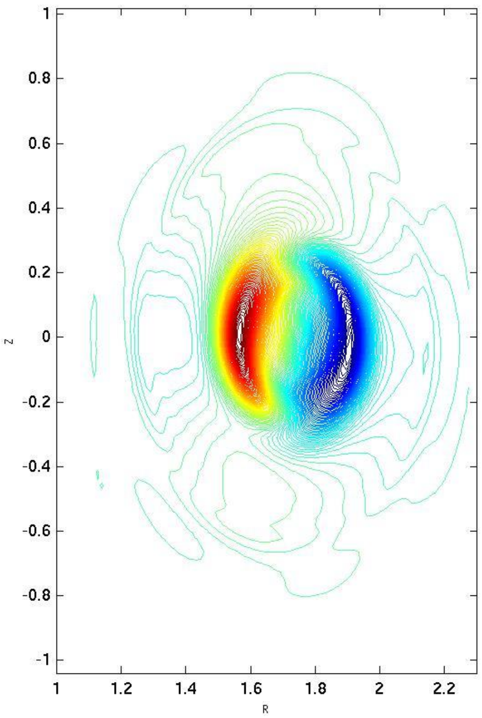
$$q(0) = 0.9$$
$$R_0 = 1.63m$$
$$a = 0.62m$$
$$B_0 = 1.9T$$
$$n_0 = 5.62 \times 10^{19} m^{-3}$$
$$Te(0) = 2.5kev$$
$$\beta(0) = 5.2\%$$
$$\beta_{beam}(0) = 1.7\%$$

Linear hybrid simulation with energetic particles shows a fishbone-like mode with finite frequency

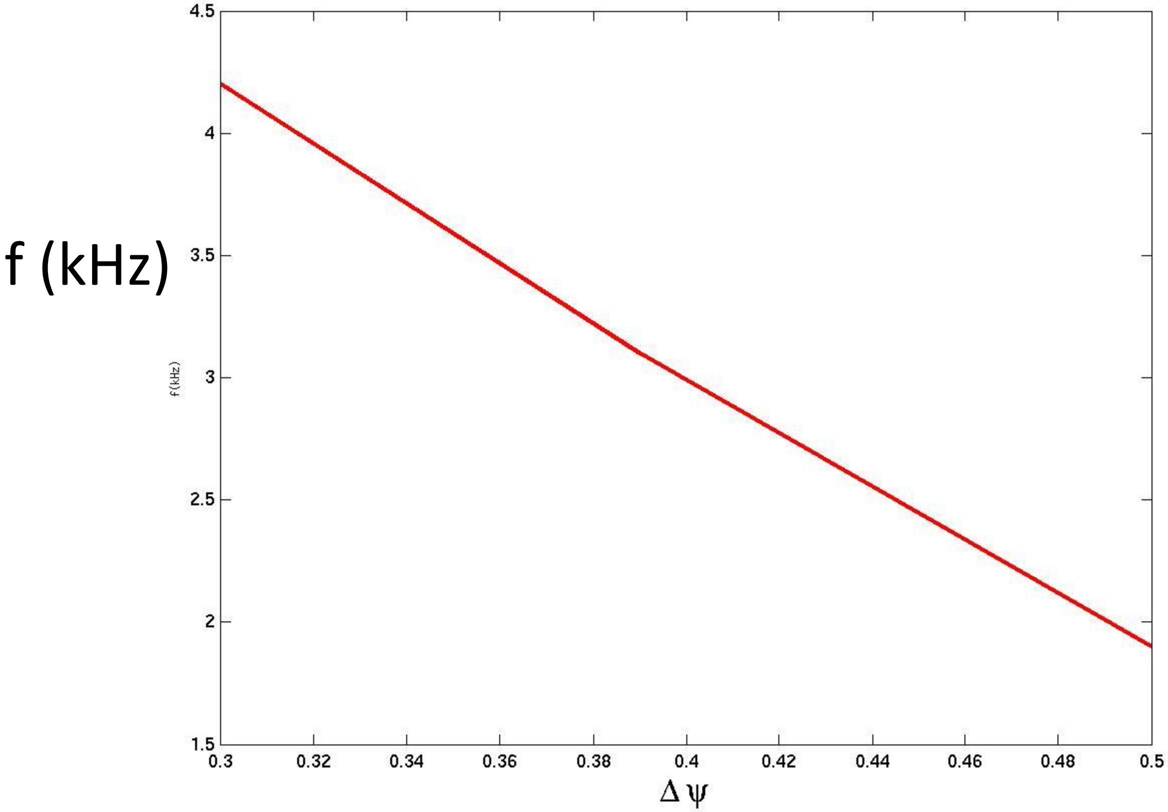
MHD kink



fishbone



The fishbone mode frequency is smaller for broader beam ion radial profile



$$f_{beam} \sim \exp\left(-\frac{\psi}{\Delta \psi}\right)$$

Future work: Effects of runaway electrons on MHD modes in JET

H.S. Cai, G.Y. Fu

Use M3D-K to investigate the MHD stability of runaway plasmas and runaway confinement

A component of runaway electrons will be added to the M3D-K code

Future work: simulation of alpha-driven TAEs in ITER

G.Y. Fu, N. Gorelenkov, R. Budny, F. Poli et al.

- DOE OFES 2014 Theory Milestone

"Understanding alpha particle confinement in ITER, the world's first burning plasma experiment, is a key priority for the fusion program. In FY 2014, determine linear instability trends and thresholds of energetic particle-driven shear Alfvén eigenmodes in ITER for a range of parameters and profiles using a set of complementary simulation models (gyrokinetic, hybrid, and gyrofluid). Carry out initial nonlinear simulations to assess the effects of the unstable modes on energetic particle transport."

Codes involved: GEM, GTC, GYRO, M3D-K, TAEFL, NOVA-K

Collaborators: Y. Chen, Z. Lin, E. Bass, D. Spong et al.

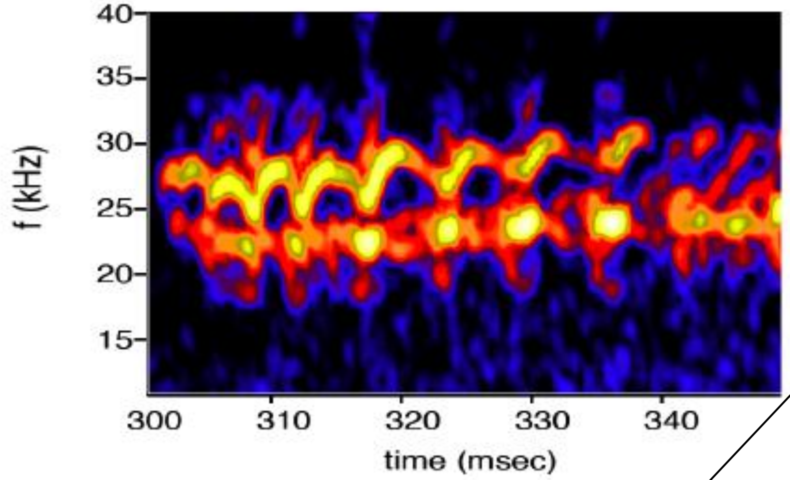
Interaction of EGAM and plasma micro-turbulence

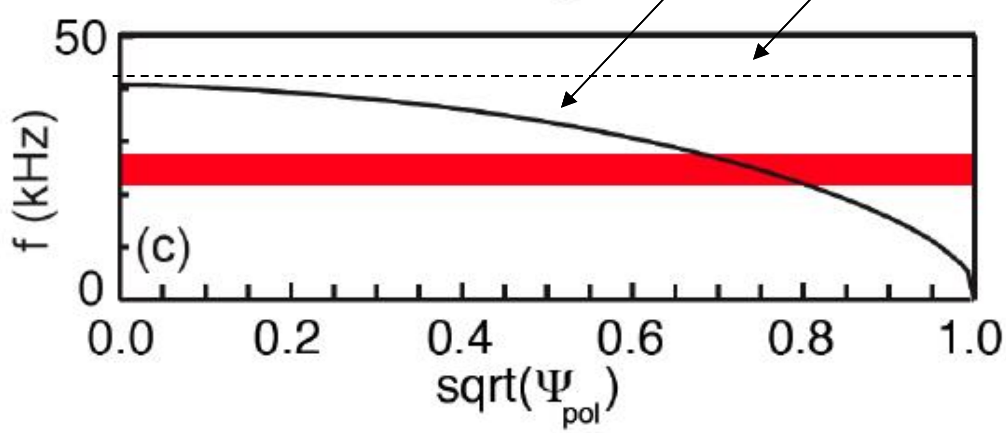
G. Wang, G.Y. Fu, W.X. Wang

- plasma background micro-turbulence can cause anomalous radial diffusion of energetic particles.
- Recent M3D-K simulations show that the turbulence-induced diffusion can have a significant effect on nonlinear saturation of fast ion-driven Alfven instability.
- Energetic particle instabilities may influence plasma micro-turbulence via EP-induced zonal flow/zonal current as well as GAM.
- GTS code will be used to simulate energetic particle-driven GAM (EGAM) and its interaction with plasma micro-turbulence

Mode Frequency Well Below ideal GAM frequency

$\delta B/B \sim 10^{-5}$, n=0 at wall



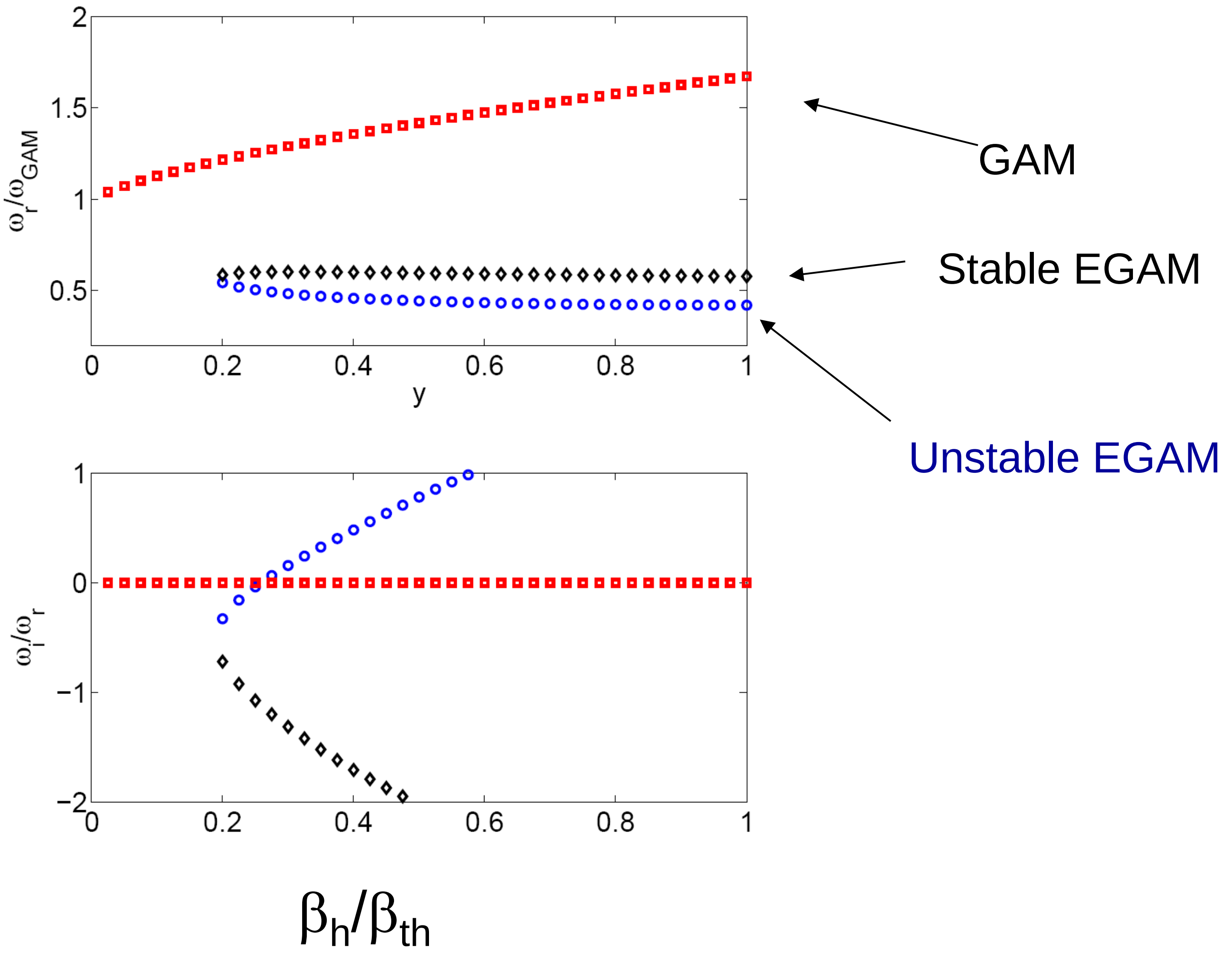


- n=0 GAM continuum
  $\omega \approx 2C_s/R$
- ideal GAM can only exist above the continuum
  - no NOVA solution
- Mode frequencies well below peak in the continuum
  - not the ideal GAM
- Mode structure is global, not the local kinetic GAM

R. Nazikian et al., Phys. Rev. Lett. 101,185001 (2008).)

DIII-D NATIONAL FUSION FACILITY

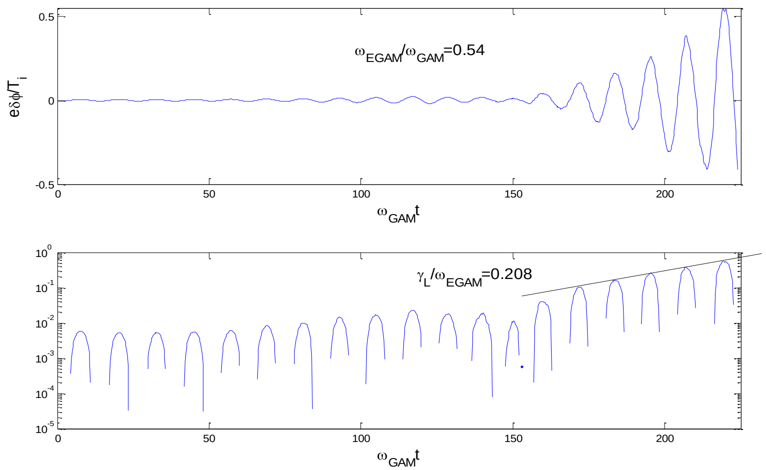
Energetic particle effects induce two new branches of eigenmode (EGAM)



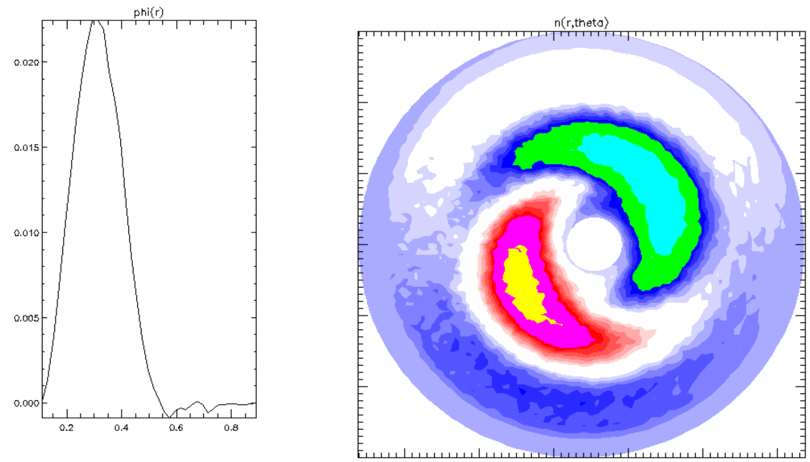
G.Y. Fu, Phys. Rev. Lett. 101,185002 (2008))

First successful simulation EGAM using GTS

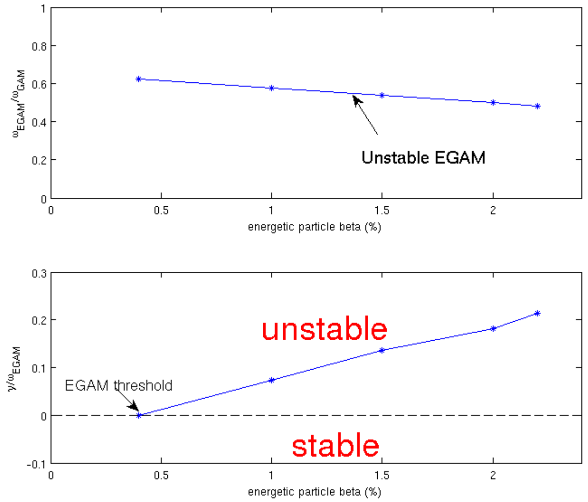
- A linear EGAM is observed in our new developed fully kinetic GTS code including the energetic particle species.



EGAM signal



(0,0) potential and (0,1) density EGAM mode structure



- The excitation threshold of EGAM on the energetic particle's beta is found in the simulation. The linear mode structure is significantly changed below the threshold.