Simulations of fishbones and Energetic Particle Modes in the EAST tokamak

Wei Shen[1], Liqing Xu[1], G. Y. Fu[2], Zhenzhen Ren[3], Feng Wang[4], Liqun Hu[1], Nong Xiang[1], Dingzong Zhang[5] and the EAST team

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, China

[2]University of Science and Technology of China, Hefei, Anhui 230026, China[3]Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, China

[3]School of Physics and optoelectronics engineering, Anhui University, Hefei, Anhui 230039, China

[4]School of Physics, Dalian University of Technology, Dalian 116024, China

[5]College of Physics and Electronic Engineering, Hengyang Normal University, Hengyang 421008, China

***E-mail: shenwei@ipp.ac.cn**

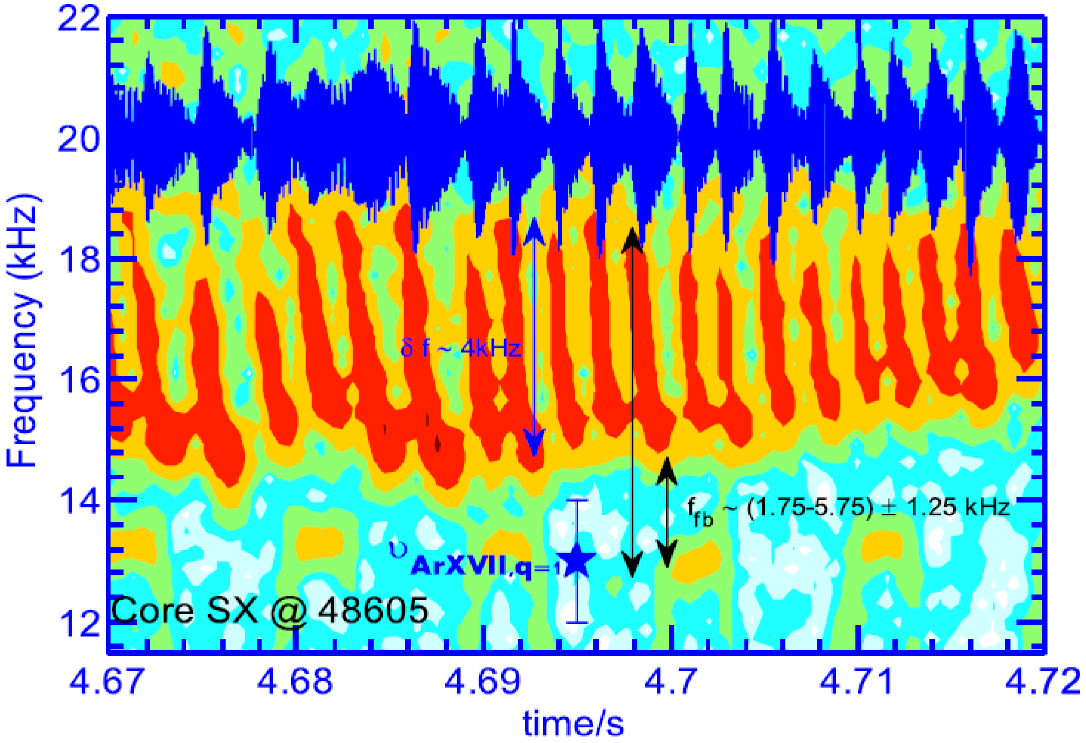
Outline

- Introduction
- Simulation of fishbones with reversed safety factor profile
- Simulation of EPMs and TAEs in EAST
- Summary

ASIPP

Introduction I

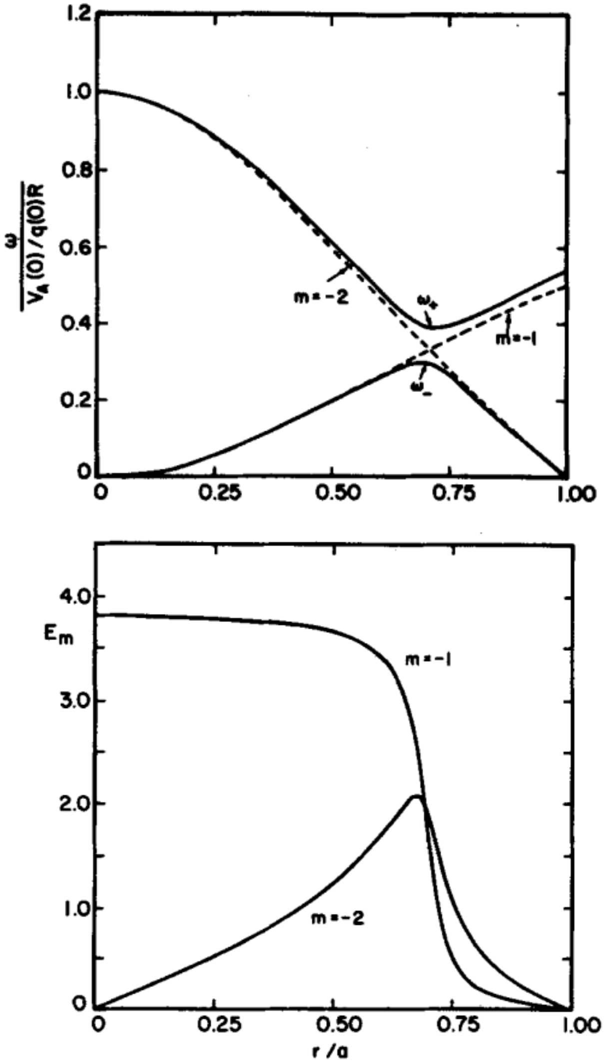
- Energetic particle driven instabilities, such as Energetic Particle Modes and various Alfvén eigenmodes, can induce energetic particle loss, degrade fast particle confinement, and even lead to serious damage of the first wall.
- Fishbone, one kind of Energetic Particle Modes, was first discovered in PDX with NBI[K. McGuire et al. PRL 1983], which is typically an internal mode with toroidal mode number n = 1 and dominant poloidal mode number m = 1.



L. Q. Xu et al. POP 2015

Introduction II

- One of the main candidates causing the anomalous transport of energetic particles is Toroidal Alfvén eigenmodes (TAEs). TAEs are discrete shear Alfvén eigenmodes which exist inside the toroidicity-induced continuum gaps[C. Z. Cheng et al. Ann. Phys. 1984].
- Instabilities driven by energetic particles including fishbones, EPMs and TAEs, are investigated numerically by M3D-K in EAST tokamak.



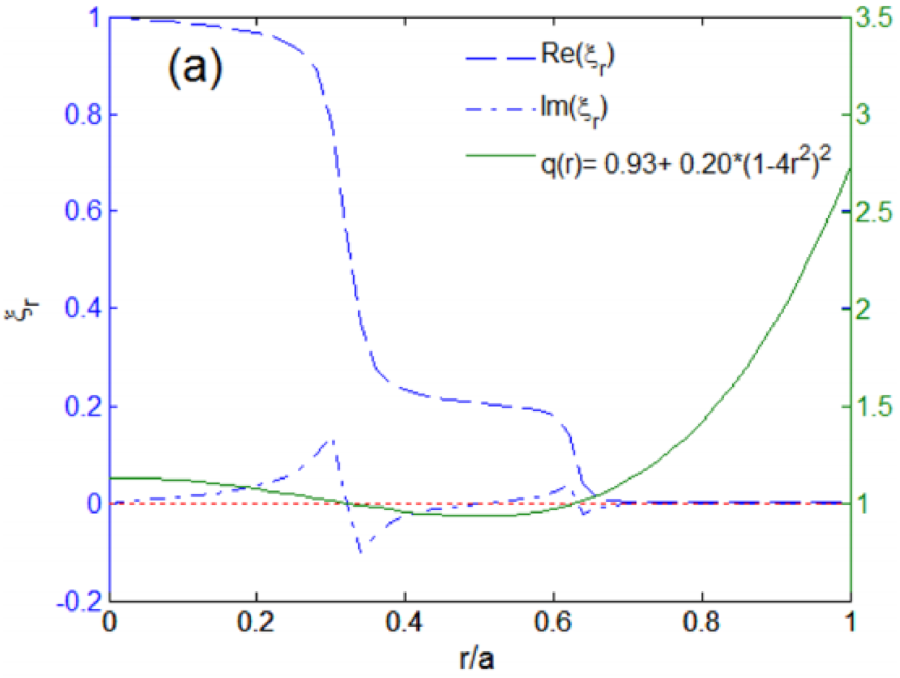
G. Y. Fu et al. Phys. Fluids B 1989

Outline

- Introduction
- Simulation of fishbones with reversed safety factor profile
- Simulation of EPMs and TAEs in EAST
- Summary

Background: fishbones with reversed q profile

- ➢ A non-monotonic safety factor profile with a reversed magnetic shear configuration has been proposed as an advanced scenario for future ITER operation.
- ➢ Two different types of fishbone: the minimum value of safety factor q_{min} is less or larger than unity.
- ✓ $q_{min} < 1$: the fishbone has been theoretically analyzed to have a two-step stucture which is similar to that of double kink modes.
- ✓ $q_{min} > 1$: the non-resonant fishbones were widely observed in both conventional tokamaks and spherical tokamaks.



G. Meng et al. POP 2015

Basic parameters and initial profiles

Main parameters: (similar to Shot #48605 on EAST)

major radius: R_0=1.86 m

minor radius: a=0.44 m

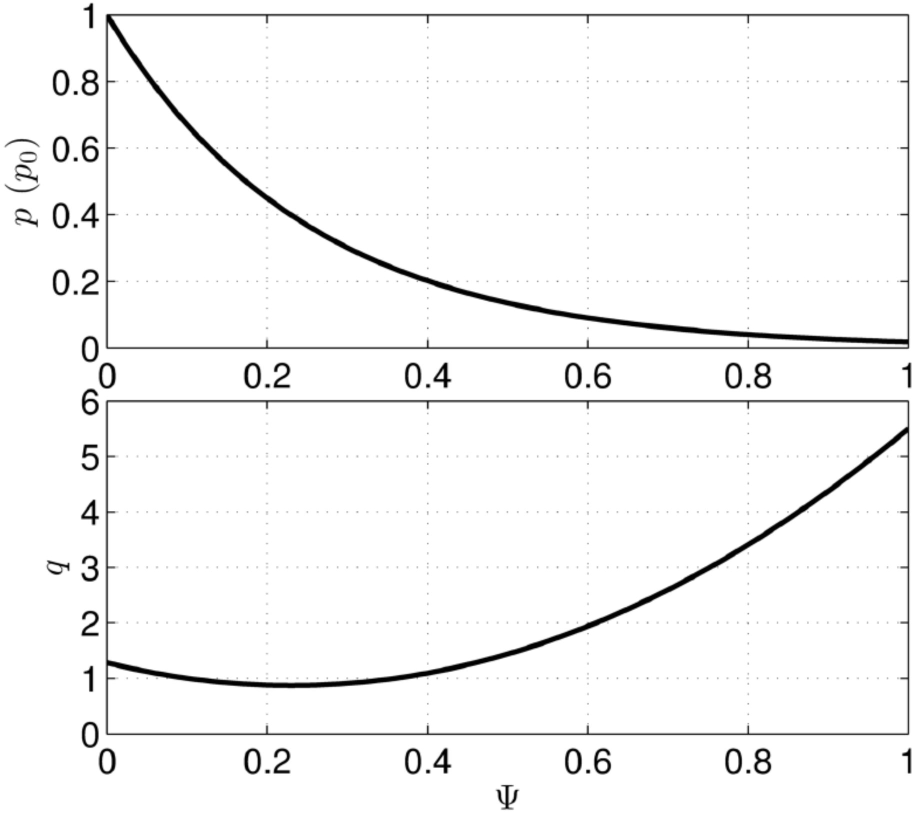
elongation: κ=1.60

triangularity: δ=0.43

toroidal magnetic field: B_0=1.75 T

central density: $n_0=5.28\times10^{19}$ m^{-3}

central total plasma beta: $\beta_{total,0}$=3.52%



Beam ion distribution function:

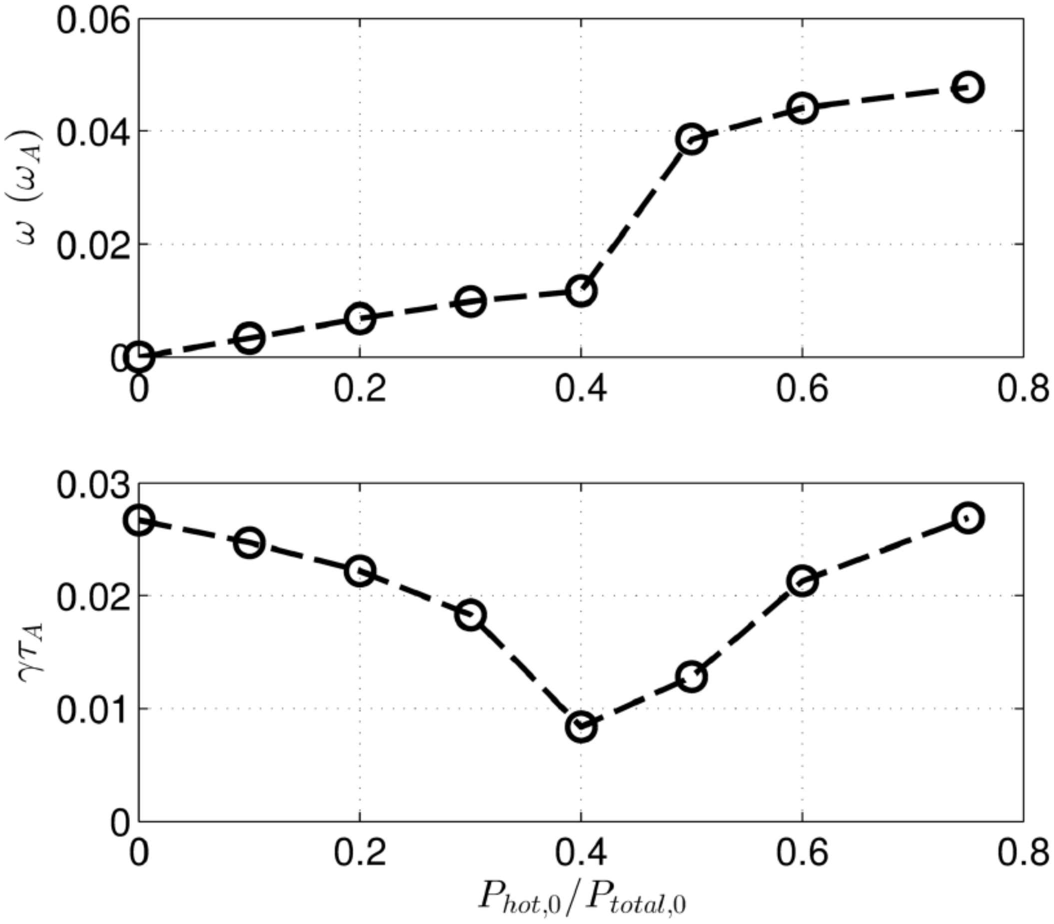
$$f = \frac{cH(v_0 - v)}{v^3 + v_c^3} \exp(-(\Lambda - \Lambda_0)^2/\Delta\Lambda^2) \exp(-\langle\Psi\rangle/\Delta\Psi),$$

$$\Lambda \equiv \mu B_0/E \qquad \Lambda_0 = 1.0,\ \Delta\Lambda = 0.2,\ \Delta\Psi = 0.3,$$

The injection energy of NBI is E_0 = 60 keV.

ASIPP

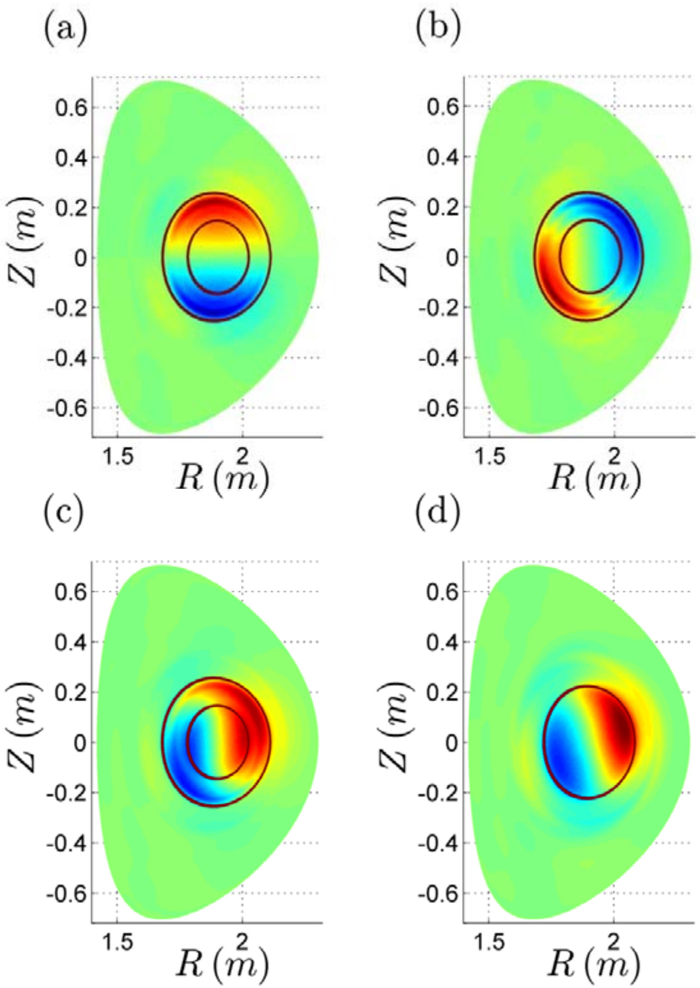
Fishbone is excited when beam pressure increases



- **$P_{hot,0}/P_{total,0}$ =0. the ideal internal kink is unstable.**
- **$P_{hot,0}/P_{total,0}$ increases from 0 to 0.4, the mode is firstly stabilized.**
- **$P_{hot,0}/P_{total,0}$ is larger than 0.4, the fishbone instability (dual resonant fishbone) is excited.**

ASIPP

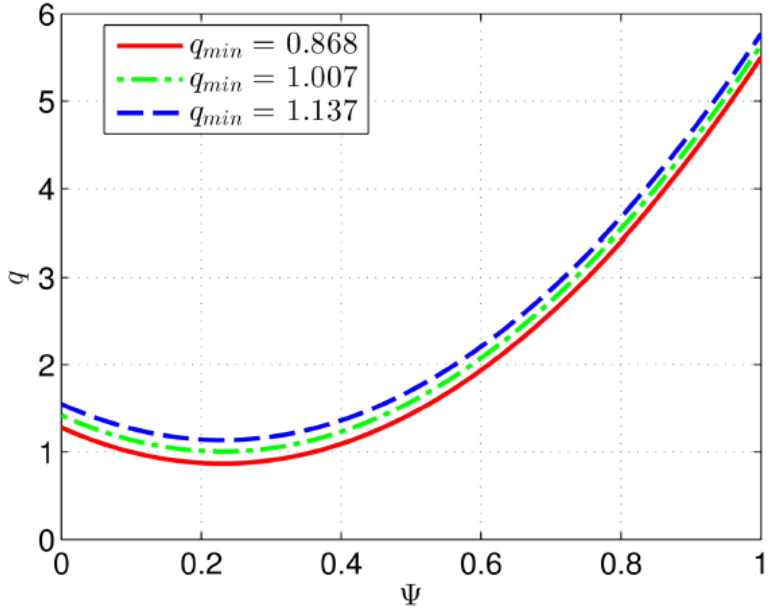
Mode structure changes when beam pressure increases

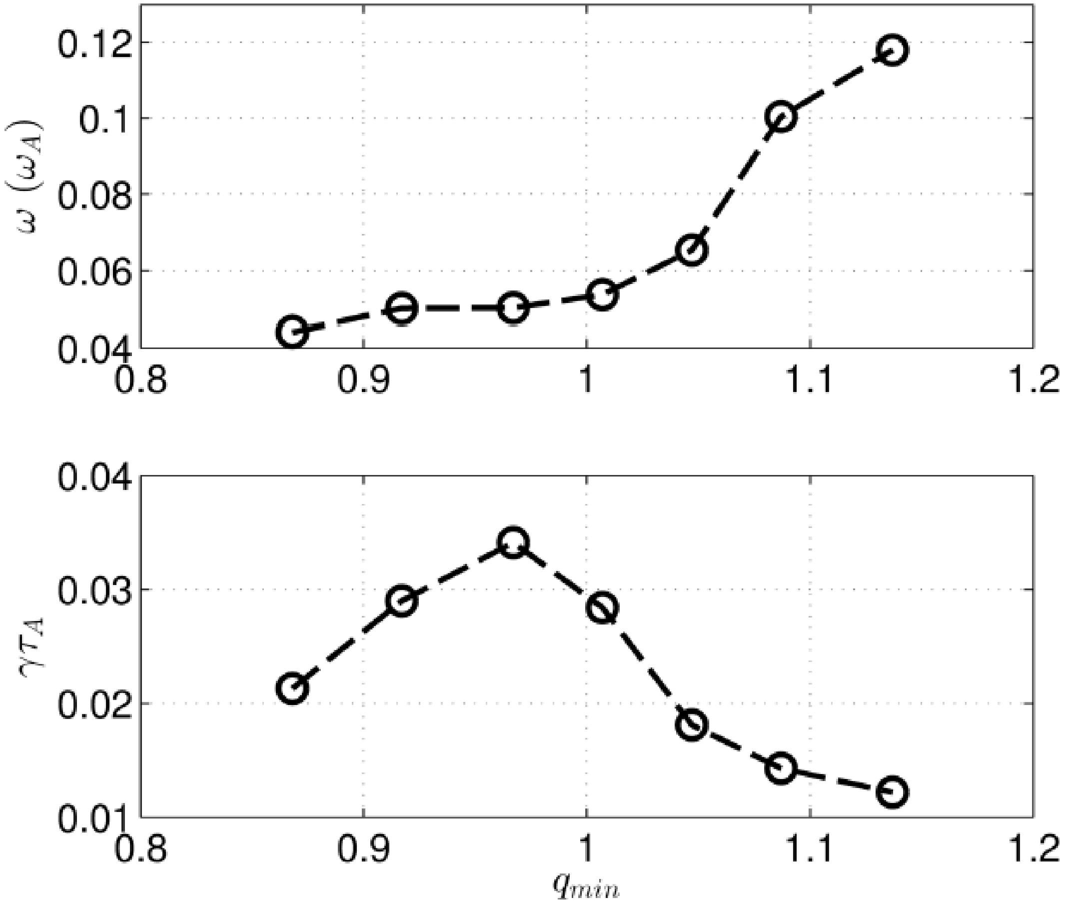


- **$P_{hot,0}/P_{total,0}=0$: up-down symmetric mode structure with splitting feature due to double q=1 surfaces (Fig. (a)).**
- **$P_{hot,0}/P_{total,0}=0.3$: the mode structure shows a twisted feature with finite mode frequency (Fig. (b)).**
- **$P_{hot,0}/P_{total,0}=0.6$: more twisted dual resonant fishbone (DRF) mode structure (Fig. (c)).**
- **$P_{hot,0}/P_{total,0}=0.6$: non-resonant fishbone (NRF) with $q_{min}=1.087$ (Fig. (d)).**

ASIPP

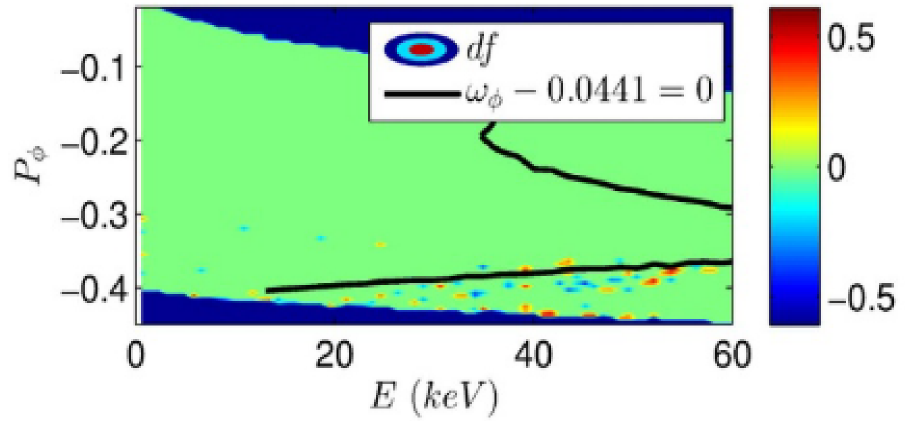
Mode changes when q_{min} changes

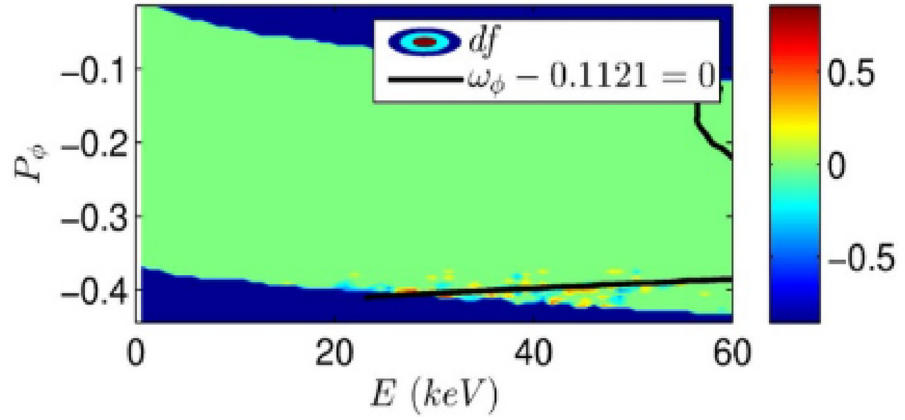




- **DRF transits to NRF with higher mode frequency.**

Large df structure is consistent with resonant condition





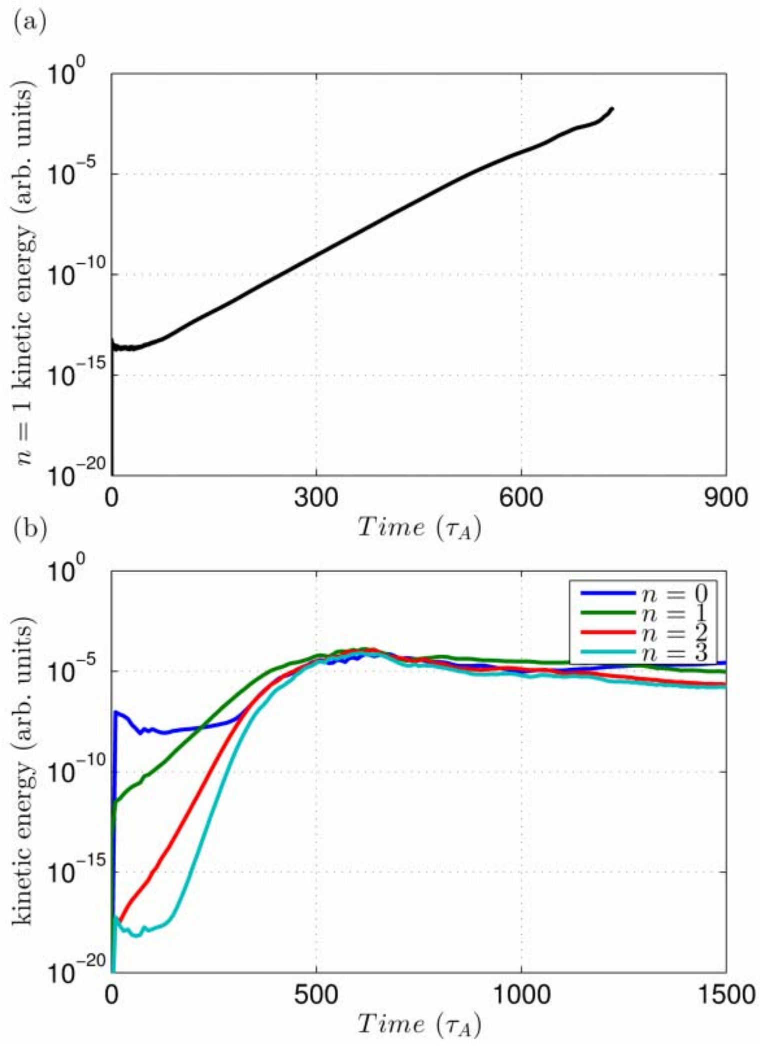
- **Resonant condition:**

$$n\omega_\phi + p\omega_\theta - \omega = 0,$$

- **For both the DRF and NRF with Λ_0=1.0, the resonant condition $\omega = \omega_\phi$ is satisfied.**

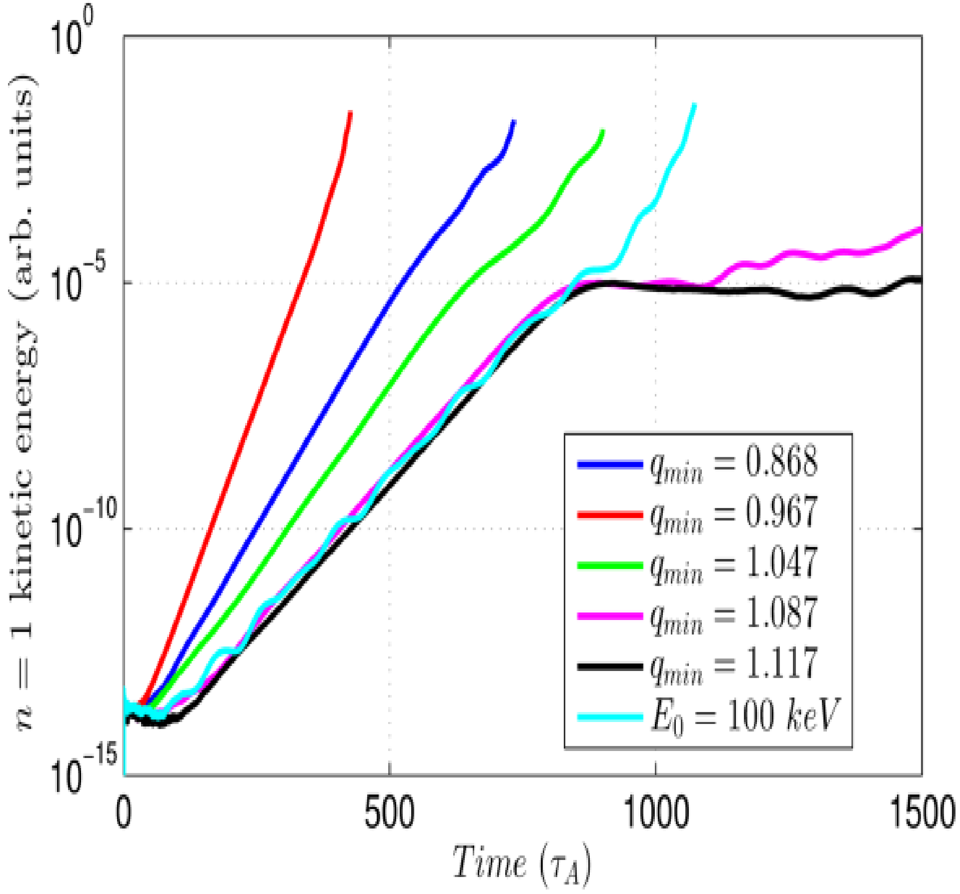
- **The energetic particles resonant with the NRF are located more centrally in radial direction, and ω_ϕ increases when the radial location decreases. As a result, the frequency of the NRF is higher than the DRF.**

Nonlinear saturation of DRF is due to MHD nonlinearity



- **The kinetic energy of the n = 1 fishbone instability does not saturate without MHD nonlinearity.**
- **With the nonlinearity of both energetic particles and MHD, the mode saturates with a large n = 0 component.**

DRF cannot saturate without MHD nonlinearity

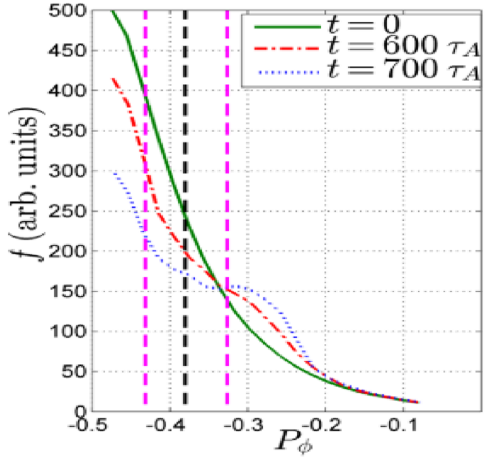


- **The figure shows the n = 1 kinetic energy with different safety factor profiles without MHD nonlinearity. The mode can saturate when $q_{min} \geq 1.087$.**
- **The cyan line shows the DRF with q_{min} = 0.868, $P_{hot,0}/P_{total,0}$ = 0.45 and E_0 = 100 keV . The DRF cannot saturate although the linear growth rate is small and almost the same with the NRFs.**

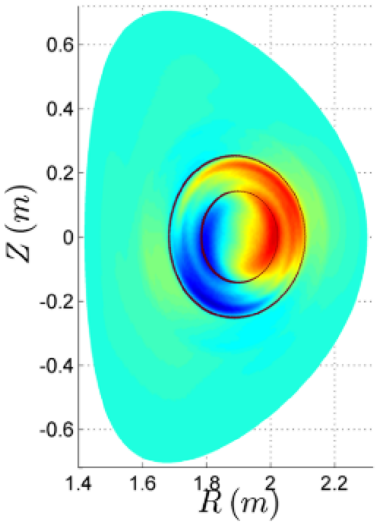
DRF cannot saturate due to steep fast ion radial gradient in the core region

- **Fast ion distribution becomes flattened in the core region due to DRF without MHD nonlinearity. However, near the magnetic axis there still exists steep fast ion radial gradient, which can drive the instability. (Fig. (a))**
- **Correspondingly, the inner m/n = 1/1 DRF mode structure shrinks in the central region at t =700 τ_A (Fig. (c)).**

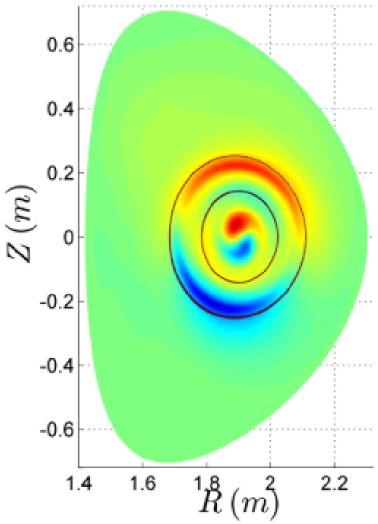
(a)



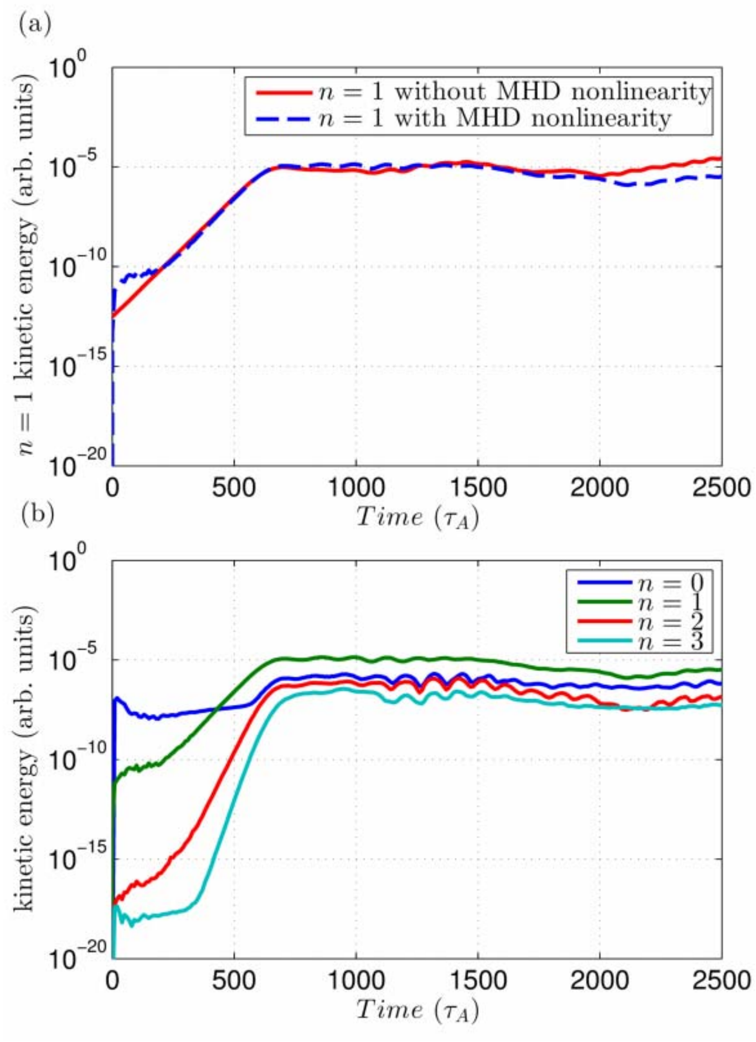
(b)



(c)

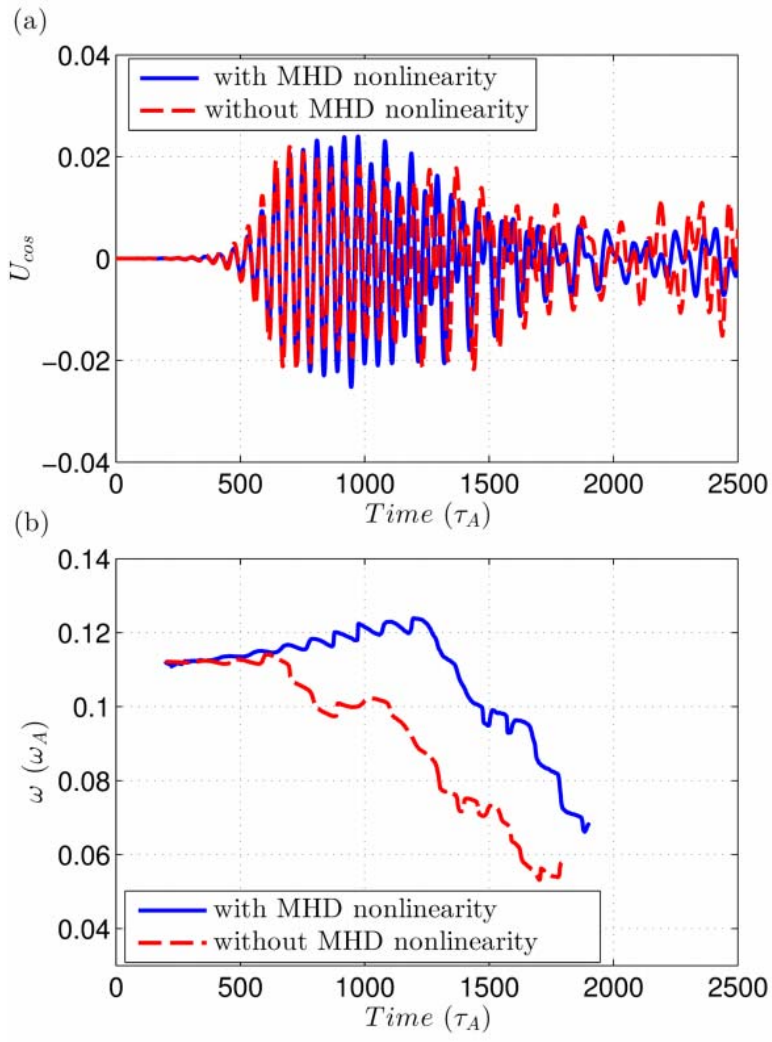


Nonlinear saturation of NRF is due to EP nonlinearity



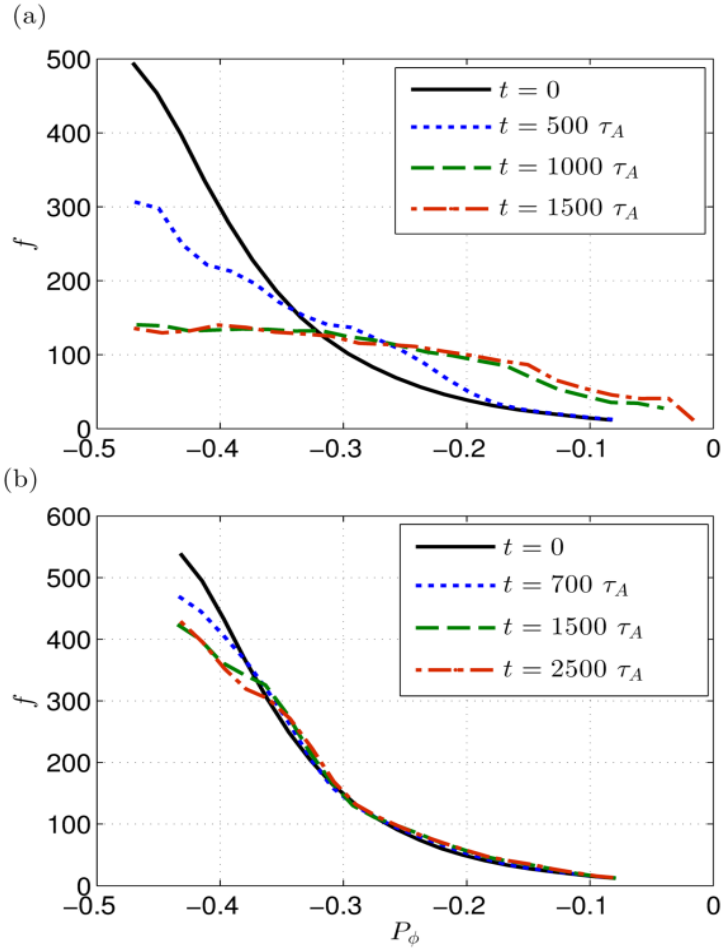
- **The saturation level of n=1 component with MHD nonlinearity is lower than that without MHD nonlinearity.**
- **Time evolution of toroidal modes up to the n = 3 mode with MHD nonlinearity is simulated. Different modes are coupled together with the n = 1 component being dominant.**

The NRF frequency chirps down during nonlinear phase



- **The frequencies of the NRFs with and without MHD nonlinearity chirp down nonlinearly.**
- **With MHD nonlinearity, the mode frequency firstly increases a little and then starts to decrease. Moreover, the averaged dω/dt during the chirping down phase is almost the same for these two NRFs.**

Fast ions are redistributed due to DRF or NRF



- **After the saturation of the DRF (at t = 500 τ_A), fast ions are strongly redistributed. Then, during the nonlinear saturation of the DRF, the distribution of the beam ions becomes flatter in the core region.**
- **In comparison with the redistribution induced by the DRF, and the redistribution level of the fast ions due to the NRF is weaker.**

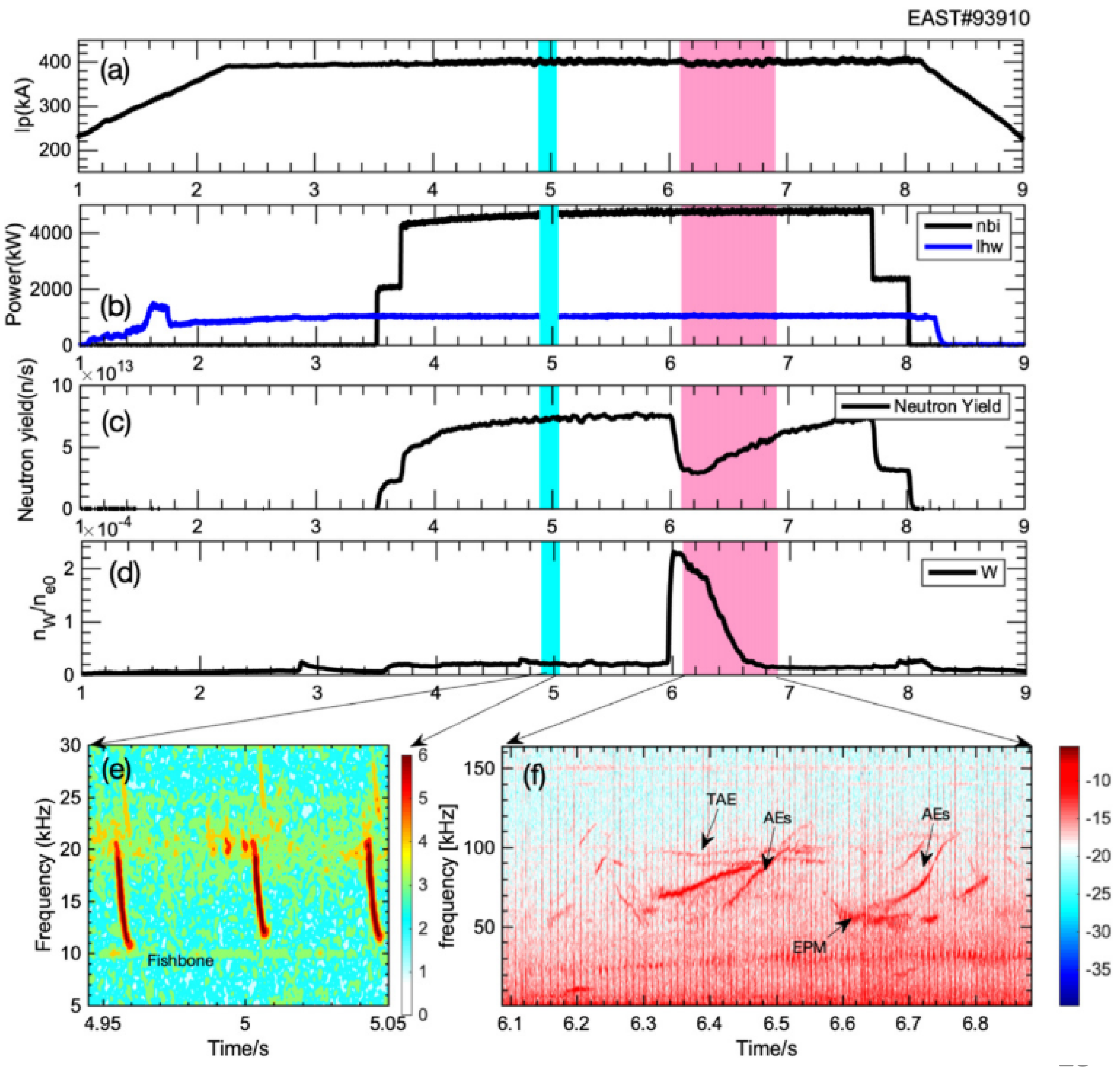
ASIPP

Outline

- **Introduction**
- **Simulation of fishbones with reversed safety factor profile**
- **Simulation of EPMs and TAEs in EAST**
- **Summary**

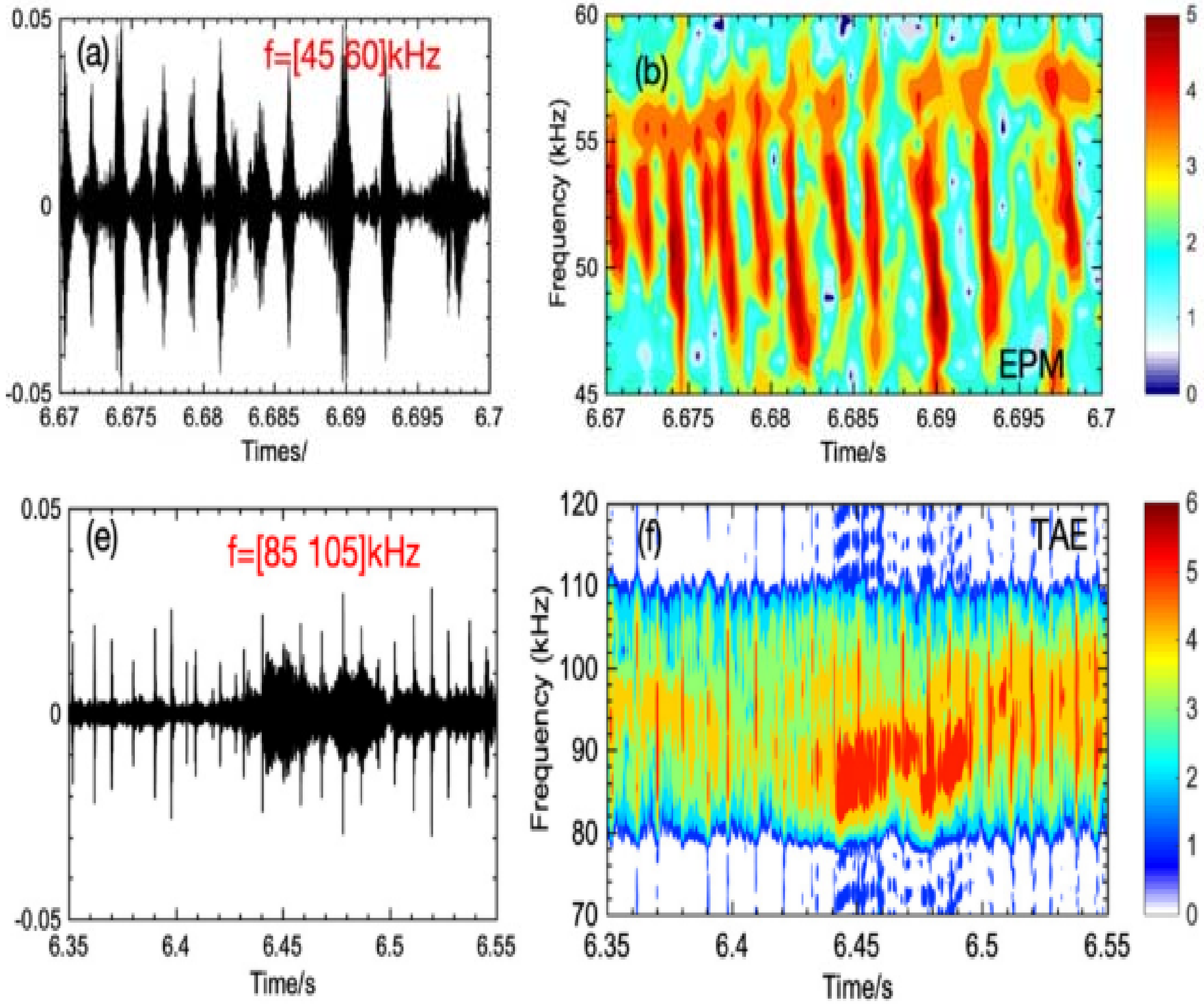
Experiment: EPMs and AEs observed in EAST

- **In EAST #Shot 93910, the auxiliary heating are is $P_{nbi} \sim 5$ MW and $P_{lhw} \sim 1$ MW.**
- **After t = 6.0 s, Alfvén eigenmodes and Energetic Particle Modes are found with NBI heating.**
- **The modes with lower frequency are identified as EPMs, and the AEs with roughly constant higher frequency are identified as TAEs by M3D-K.**



Observation of EPM to TAE

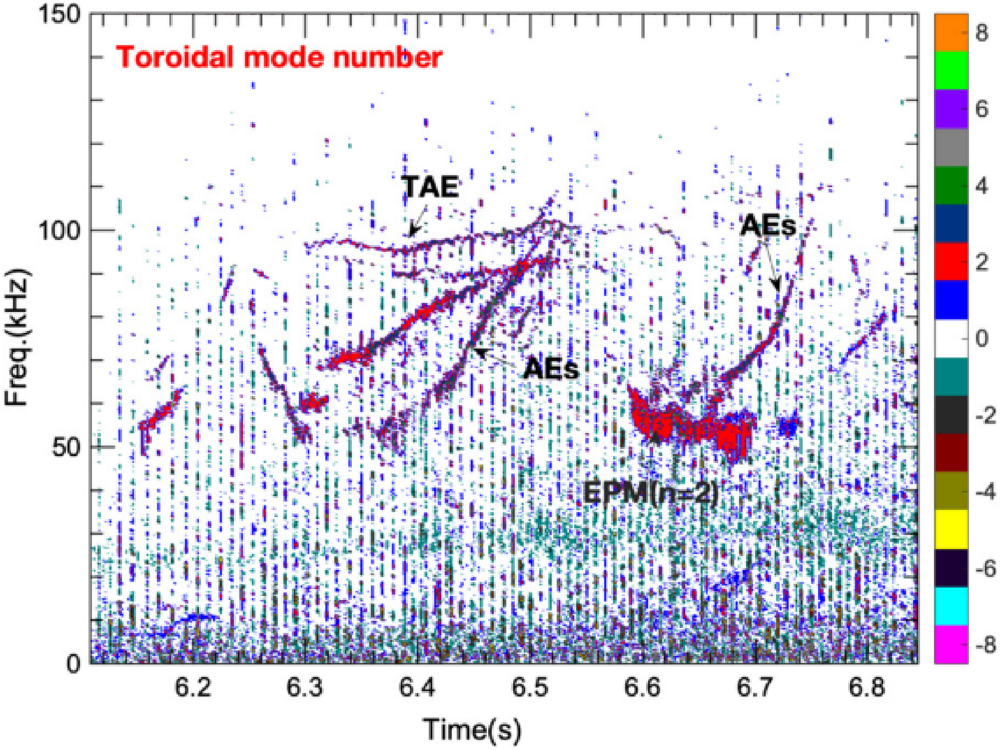
- (a) (b) EPM with frequency f ~ 60 kHz and chirps down rapidly
- (e)(f) TAE with roughly constant frequency f ~ 100 kHz

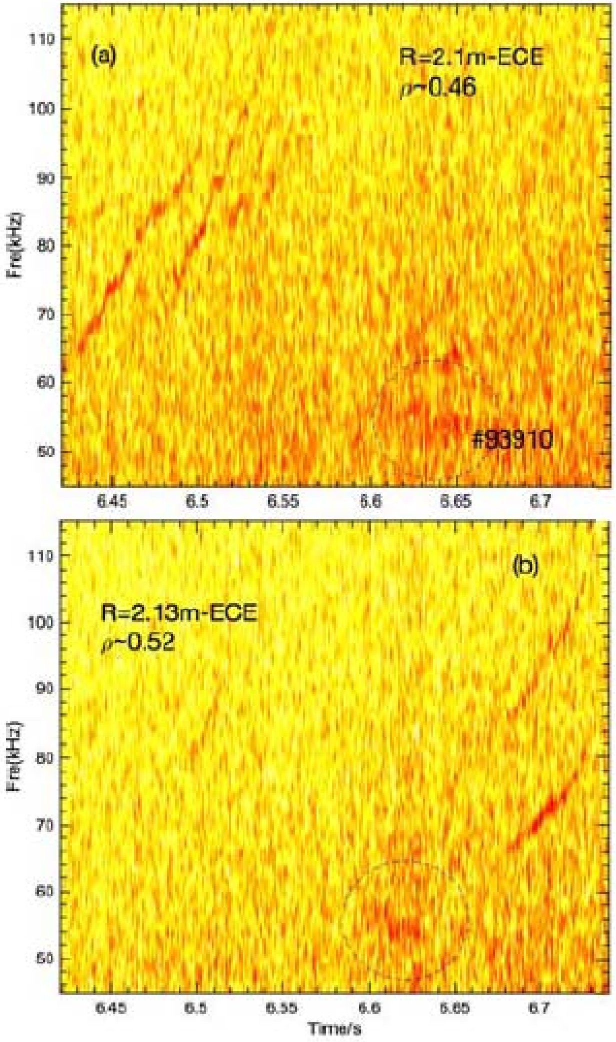


ASIPP

Identification of mode number and mode location

- The toroidal mode numbers are n=2
- The mode locations are $\rho = 0.46 - 0.52$

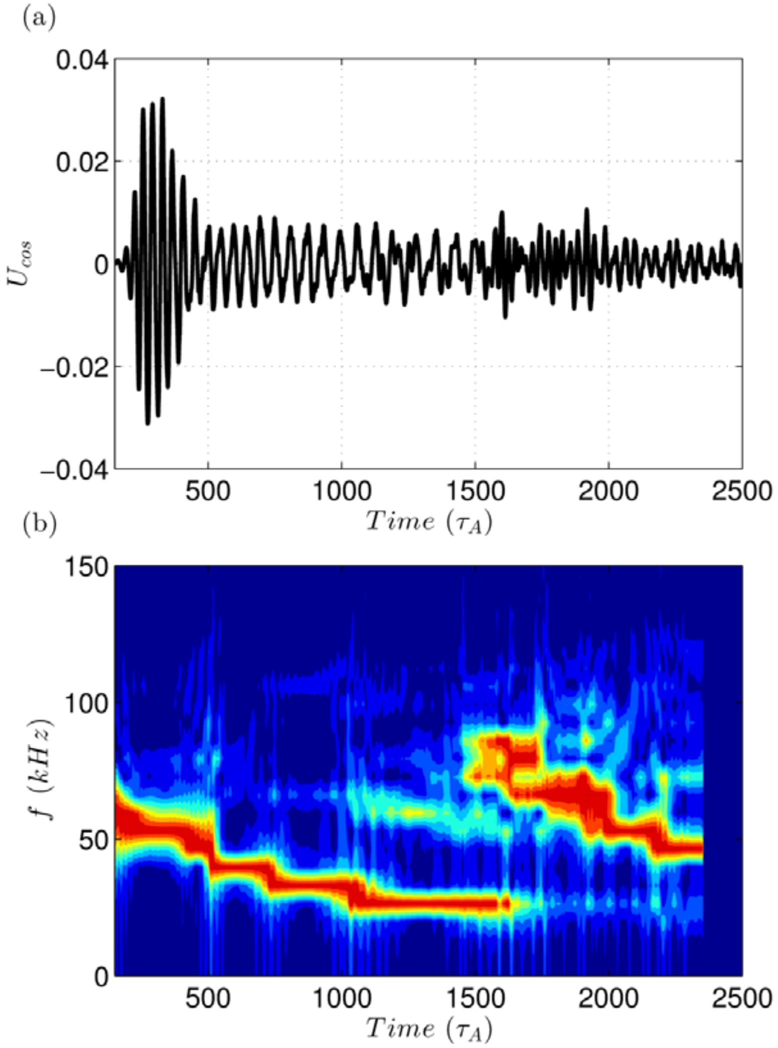




EPM chirps down and transits to TAE

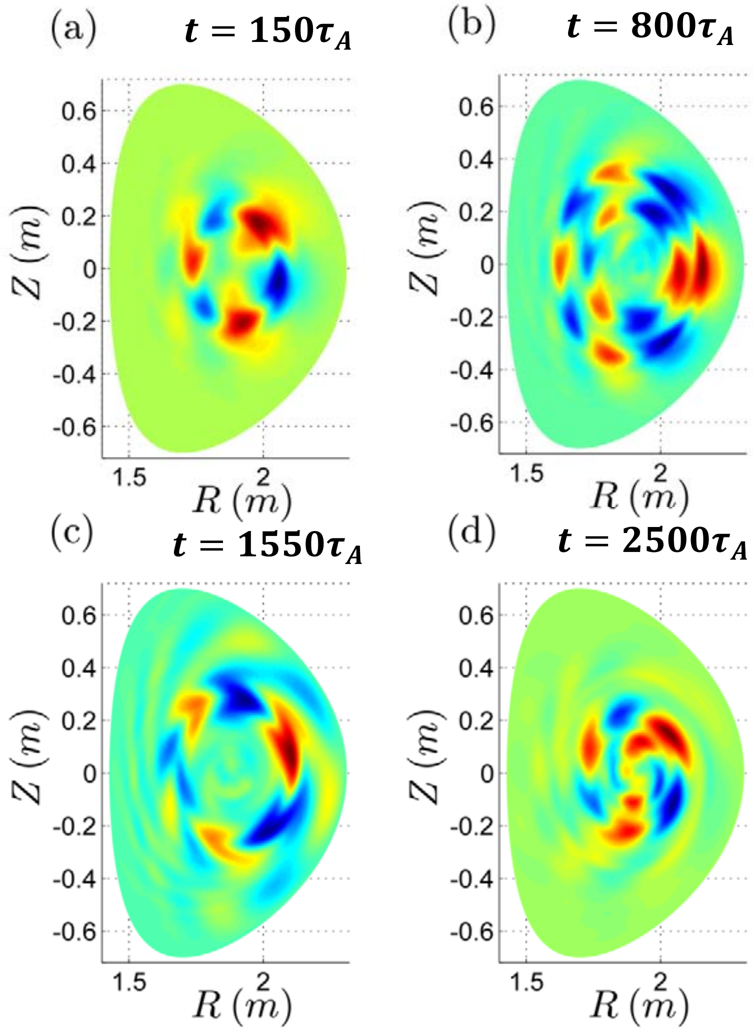
Equilibrium profiles and parameters are chosen at t=6.5 s

- **The EPM amplitude first increases to reach its maximum, and then decreases and starts to saturate.**
- **The EPM frequency chirps down from around** f=53.0 kHz**.**
- **At around** $t = 1550\tau_A$, **a TAE with around** f=88.0 kHz **emerges.**



EPM transits to TAE nonlinearly

- **Fig. (a):** Linearly a m=3, n=2 EPM is excited at around $\rho = 0.46$.
- **Fig. (b):** Double mode structures are found during chirping down phase.
- **Fig. (c):** a TAE emerges with f=88.0 kHz, the radial location is around $\rho = 0.51$.
- **Fig. (d):** TAE disappears, and EPM chirps down continuously.

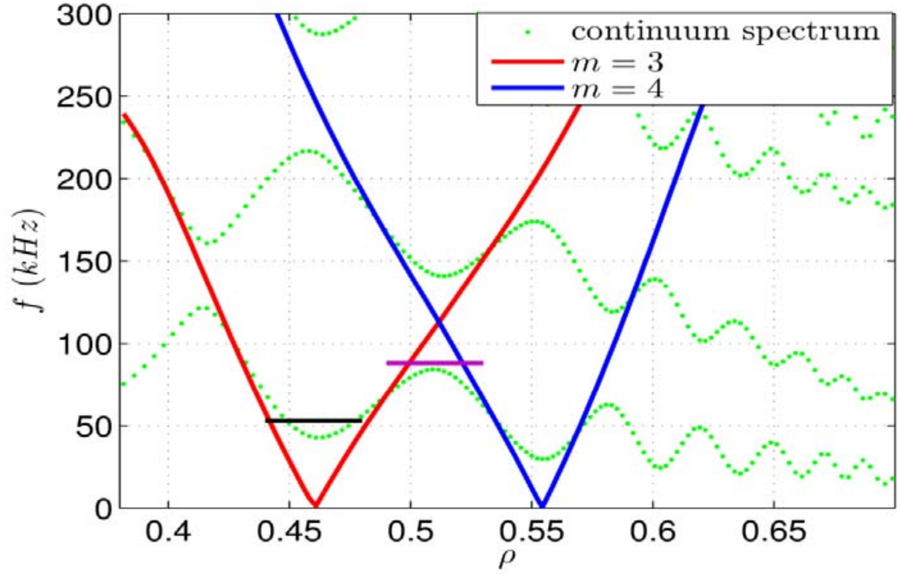


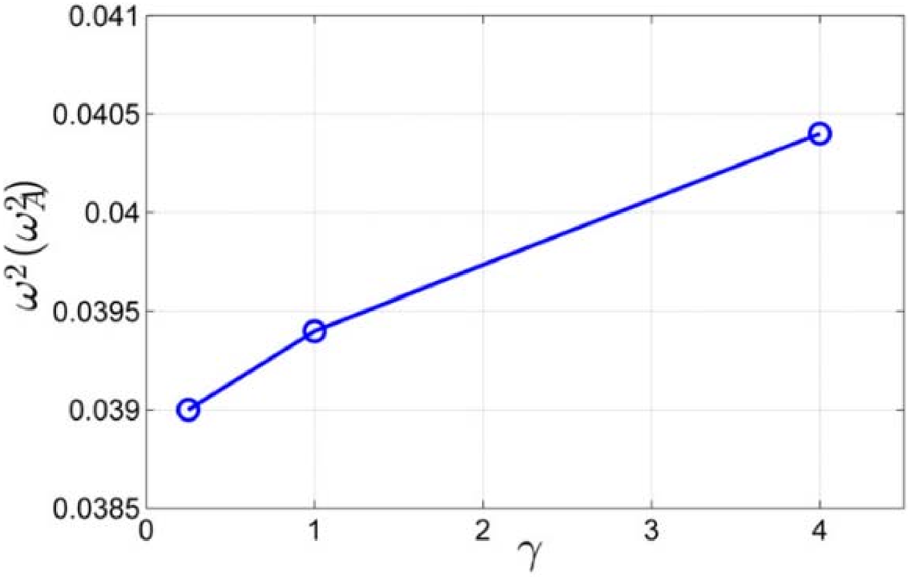
ASIPP

The EPM and TAE are verified numerically

- **The mode at around t=1550τ_A is inside the TAE gap which is formed due to the coupling between the m=3 and m=4 poloidal harmonics.**
- **The linear EPM mode is just a little above the** m=3 **BAE gap, and the mode frequency is almost unchanged with the variation of γ.**

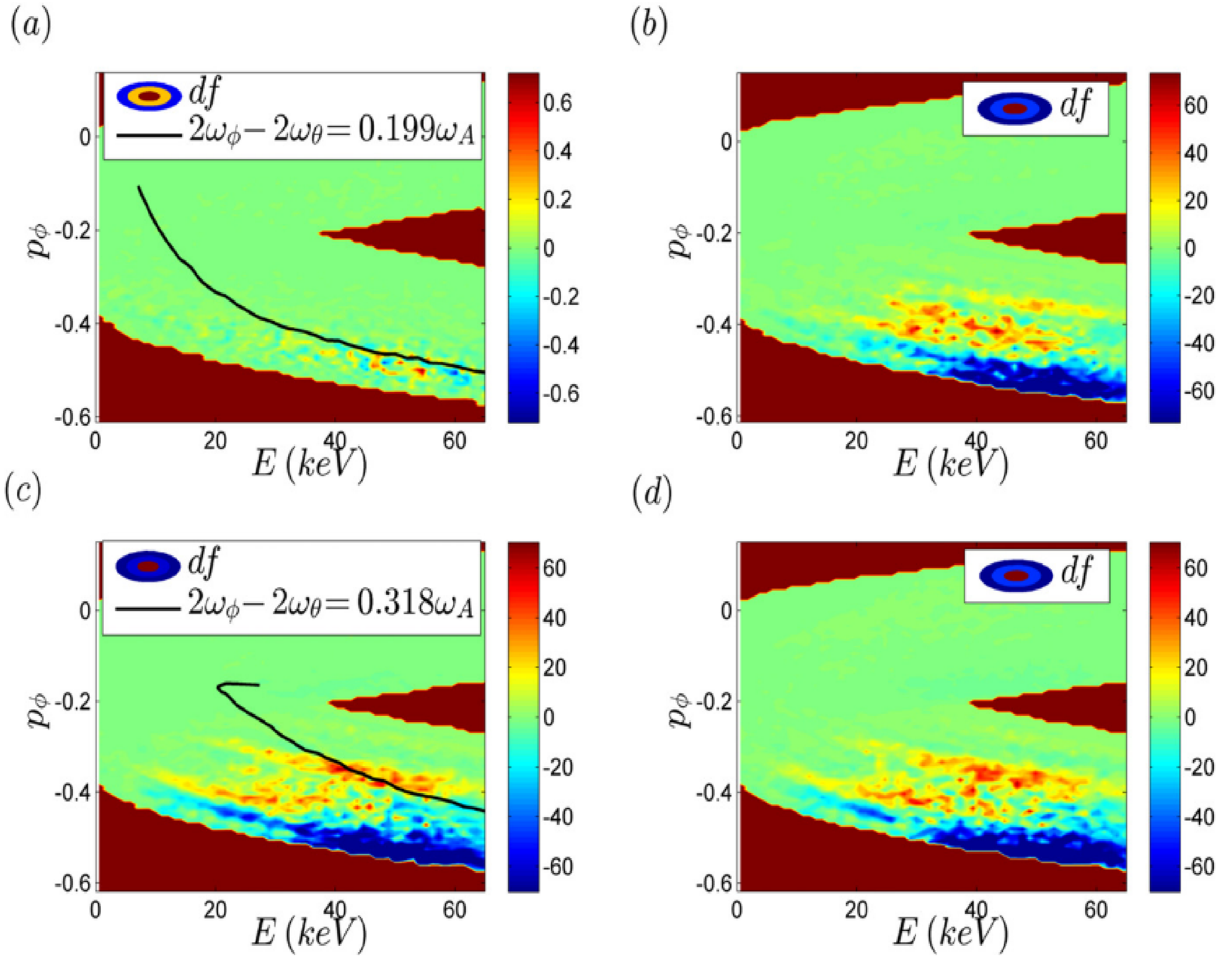
$$\omega_{\rm BAE} = \sqrt{\gamma\beta}\,\omega_{\rm A}$$





Fast ions are strongly redistributed due to EPMs

- In the linear phase (fig. (a) at $t = 150\tau_A$), the large df structure is consistent with the resonant condition $2\omega_\phi - 2\omega_\theta - 0.199\omega_A = 0$
- In the later nonlinear phase when the high frequency TAE emerges (fig. (c) at $t = 1600\tau_A$), the corresponding resonant condition $2\omega_\phi - 2\omega_\theta - 0.318\omega_A = 0$ is located at the boundary of the flattening region of beam ions, as the excitation of TAE needs the radial gradient of fast ions.



Outline

- Introduction
- Simulation of fishbone with reversed safety factor profile
- Simulation of EPMs and TAEs in EAST
- Summary

Summary

The fishbone instabilities, EPMs and TAEs in the EAST tokamak have been simulated by the global kinetic-MHD code M3D-K.

✓ **Fishbone with reversed q profile:**

➢ **When q_{min} increases from below unity to above unity, the fishbone transits from DRF to NRF**

➢ **The saturation of the DRF is due to MHD nonlinearity with a large n = 0 component. However, the saturation of the NRF is mainly due to the nonlinearity of fast ions.**

✓ **EPMs and TAEs**

➢ **TAEs and EPMs have been observed in EAST with NBI heating.**

➢ **The simulated mode frequencies and locations of the EPM and TAE, as well as the chirping down feature of the EPM frequency, are consistent with the experimental measurements.**

Thank you very much for your attention!