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Investigation of double frequency fishbones in EAST with neutral beam injection

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Outline

- **Background**
- **Experimetal observations**
- **Simulation results**
- **Summary**

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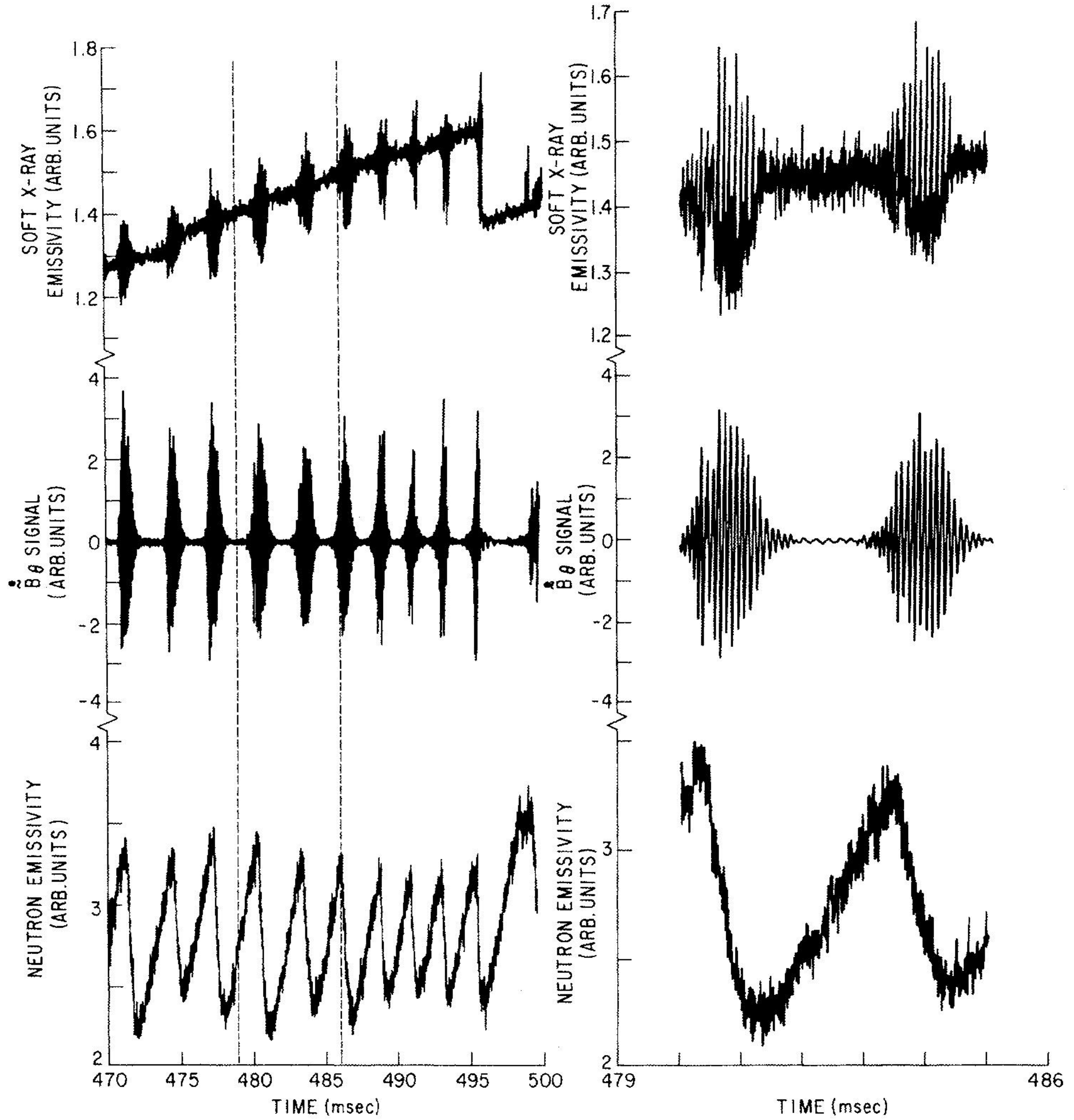
Background

- Energetic particle driven instabilities, such as fishbones and various Alfvén eigenmodes, can induce energetic particle loss, degrade fast particle confinement, and even lead to serious damage of the first wall.

- Fishbone 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.



Background: precessional fishbone

- Two theories were developed to explain the fishbone.
- Chen et al.[L. Chen et al. PRL 1983] proposed that the fishbone is driven by energetic trapped ions via precessional resonant condition $\omega = \omega_d$.
- Coppi et al.[B. Coppi et al PRL 1986] proposed that fishbone is destabilized by energetic particles through a positive dissipation process with the mode frequency on the order of ω_{*i}.
- Fishbone dispersion relation based on Chen's theory: L. Chen et al. PRL 1983

initial term fluid energetic particle

$$-i\omega/\tilde{\omega}_A + \delta\hat{W}_f + \delta\hat{W}_k = 0$$

$$\delta\hat{W}_k = \frac{\pi^2 m_h 2^{7/2}}{(r_s B_0)^2}\int_0^{r_s} r dr \int_{1-r/R}^{1+r/R} d(\alpha B)\int_0^{\infty} dE\, E^{5/2}\frac{K_2^2}{K_b}\left[\frac{Q}{\bar{\omega}_{dh}-\omega}\right]_{1,1}$$

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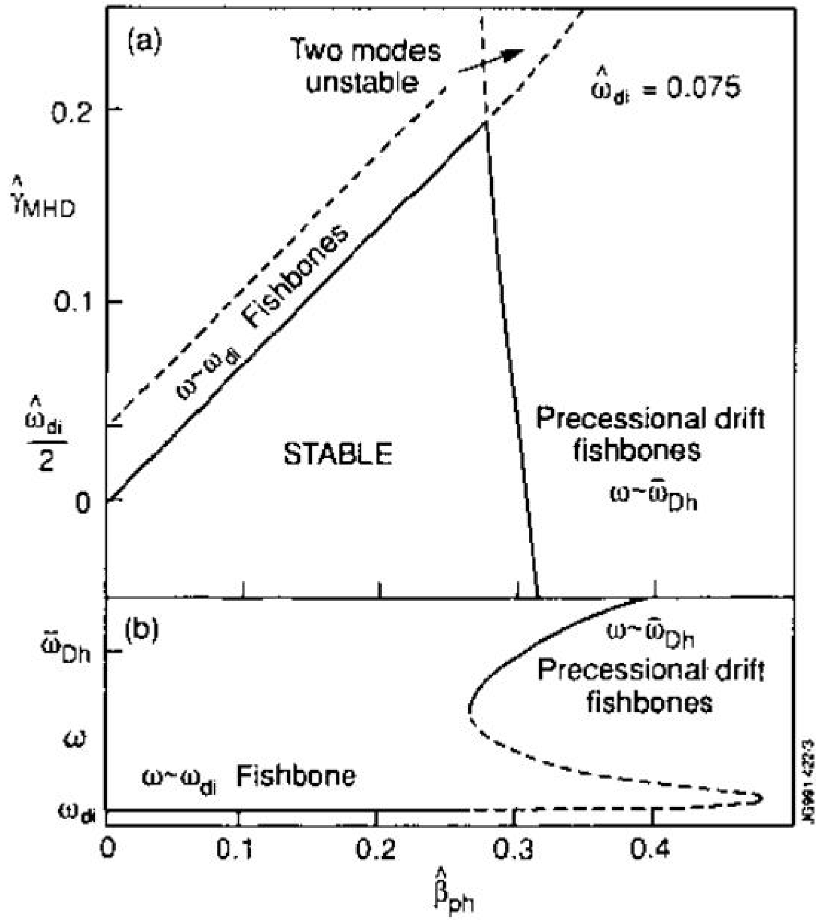
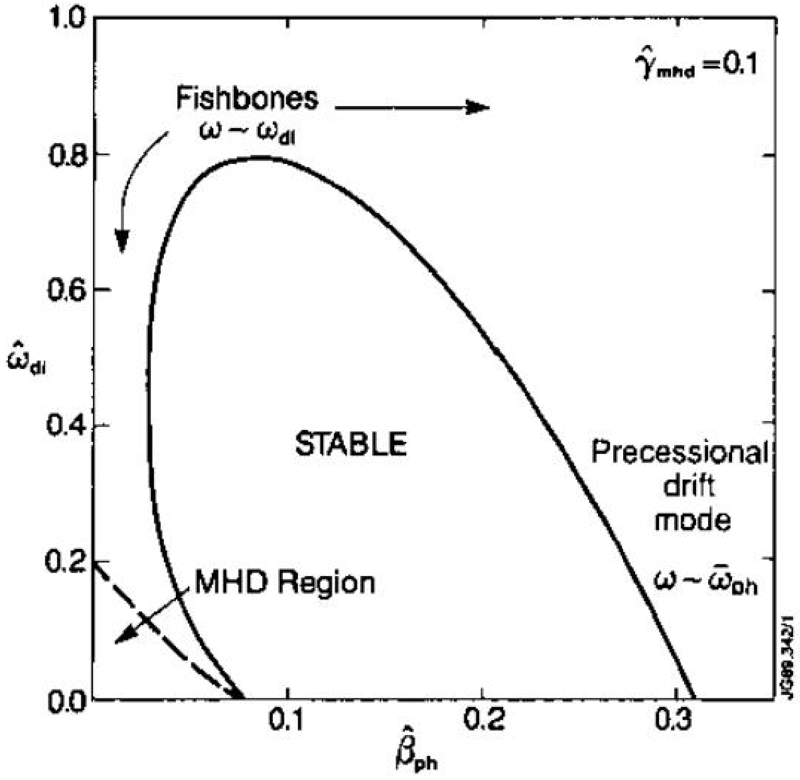
Background: stabilitiy diagram

- **Stability diagram of precessinal fishbone and diamagnetic fishbone (Porcelli, PPCF 1991)**
- **When EP beta exceeds a critial value, precessional fishbone is excited**





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Experimental setup and observations

- **In this work, the global hybrid code M3D-K is applied to analyse the fishbones with mode numbers m/n=1/1 and 2/2 observed in EAST with neutral beam injection .**

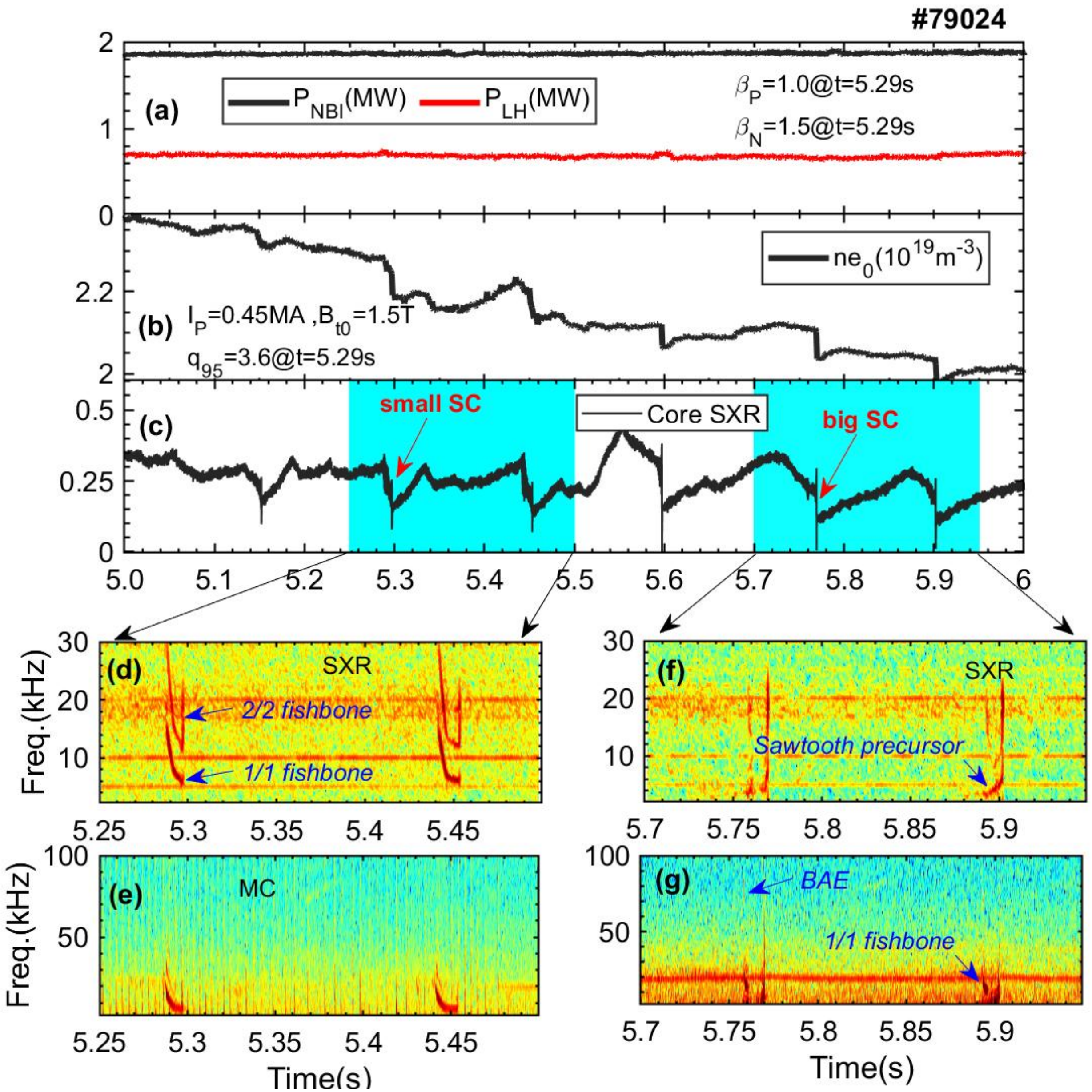
P_{NBI}~ 2 MW with injected energy 60 keV

Ip = 0.45 MA

P_{LH}~0.8 MW

Bt=1.5 T

q_{95}~3.6



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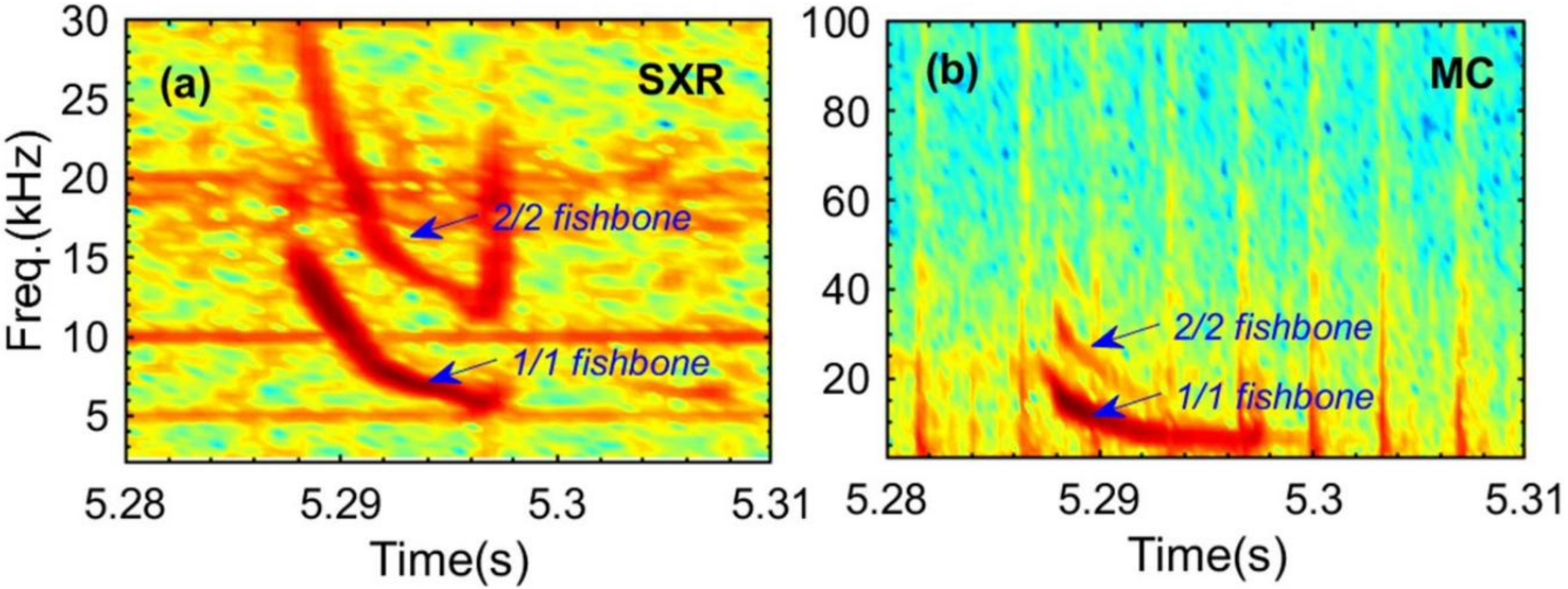
Double frequency fishbones are observed in EAST

- The presence of a fishbone mode with m/n = 2/2 that rivals the fundamental m/n = 1/1 mode. The frequency of the m/n = 2/2 mode is double of the m/n = 1/1 fishbone mode.
- The frequency of the fundamental fishbone mode undergoes a decrease from an initial f~20 kHz to f~7 kHz.



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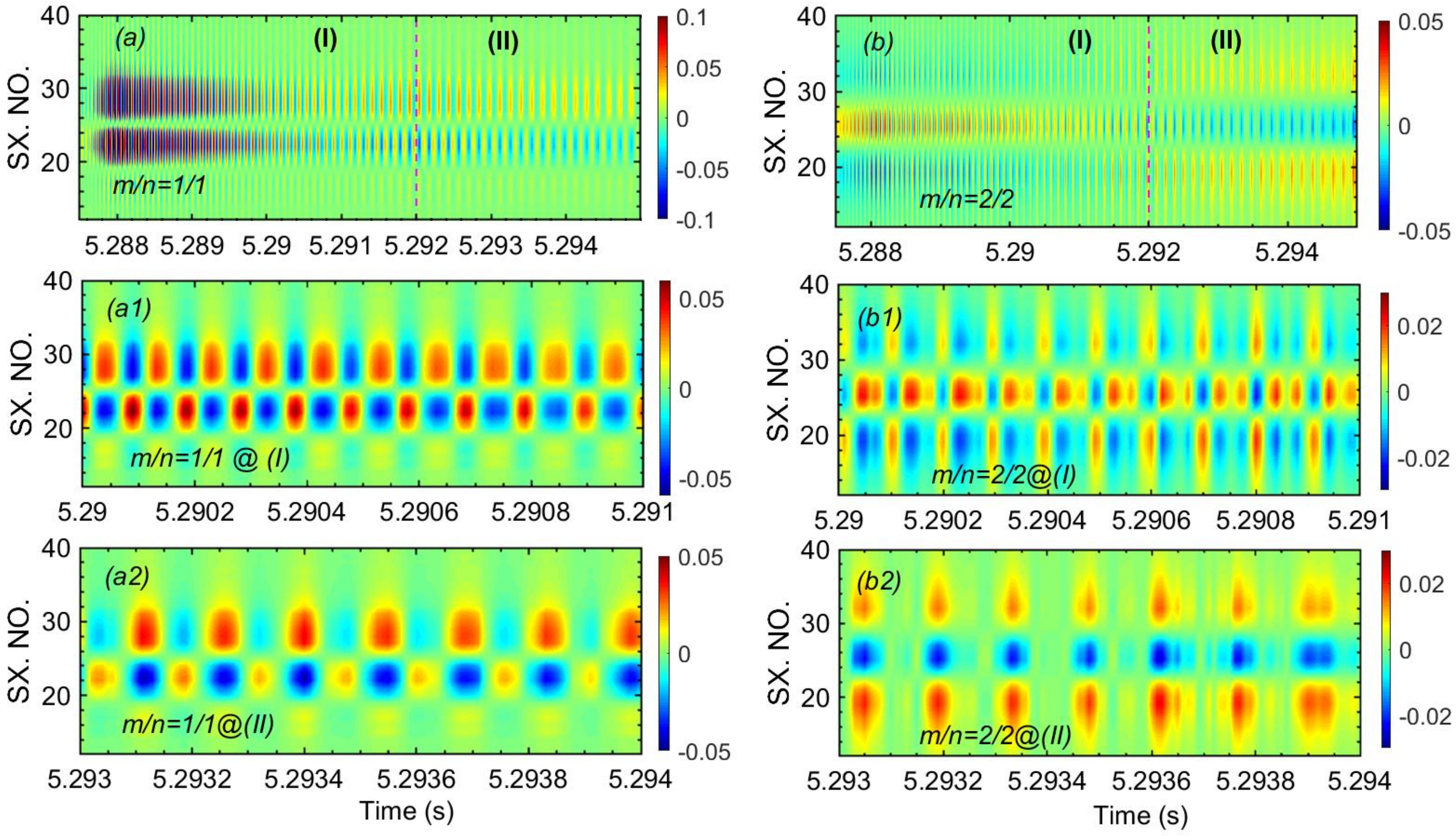
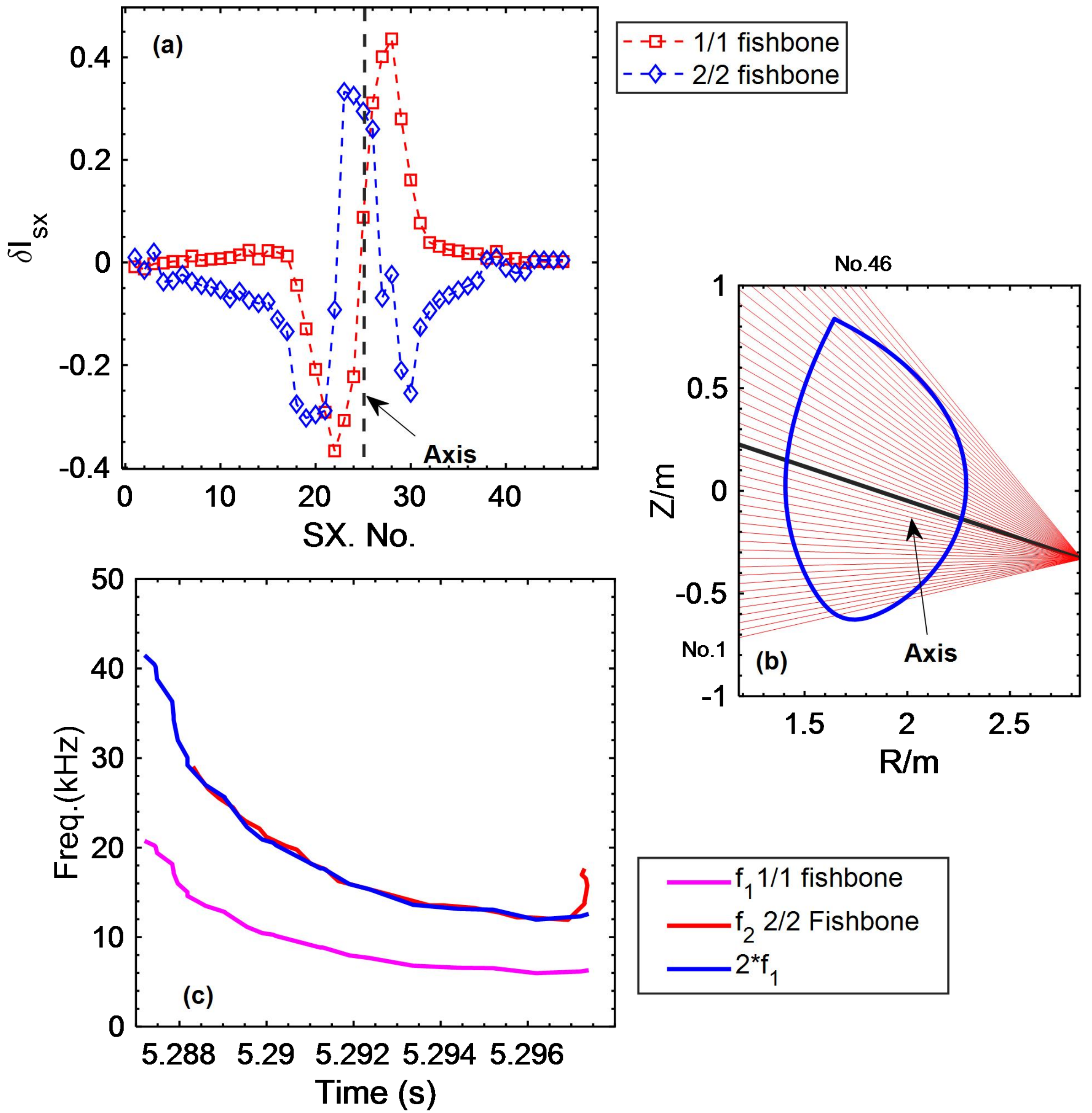
SXR structure of both m/n=1/1 and m/n=2/2 modes

- **Both modes are situated at the same radial location.**
- **phase I: m/n=1/1 amplitude is stronger than that of m/n = 2/2 mode.**
- **phase II: m/n=1/1 mode saturates, while m/n=2/2 fishbone increases**



Fishbone mode structure and frequency

- **Figure (a) shows the n = 1 mode exhibits an odd symmetry structure , whereas the n = 2 mode displays an even symmetry structure.**
- **Figure (c) shows the n = 2 fishbone mode occurs following the n = 1 fishbone mode. The frequency of the n = 2 mode is double that of the n = 1 mode**



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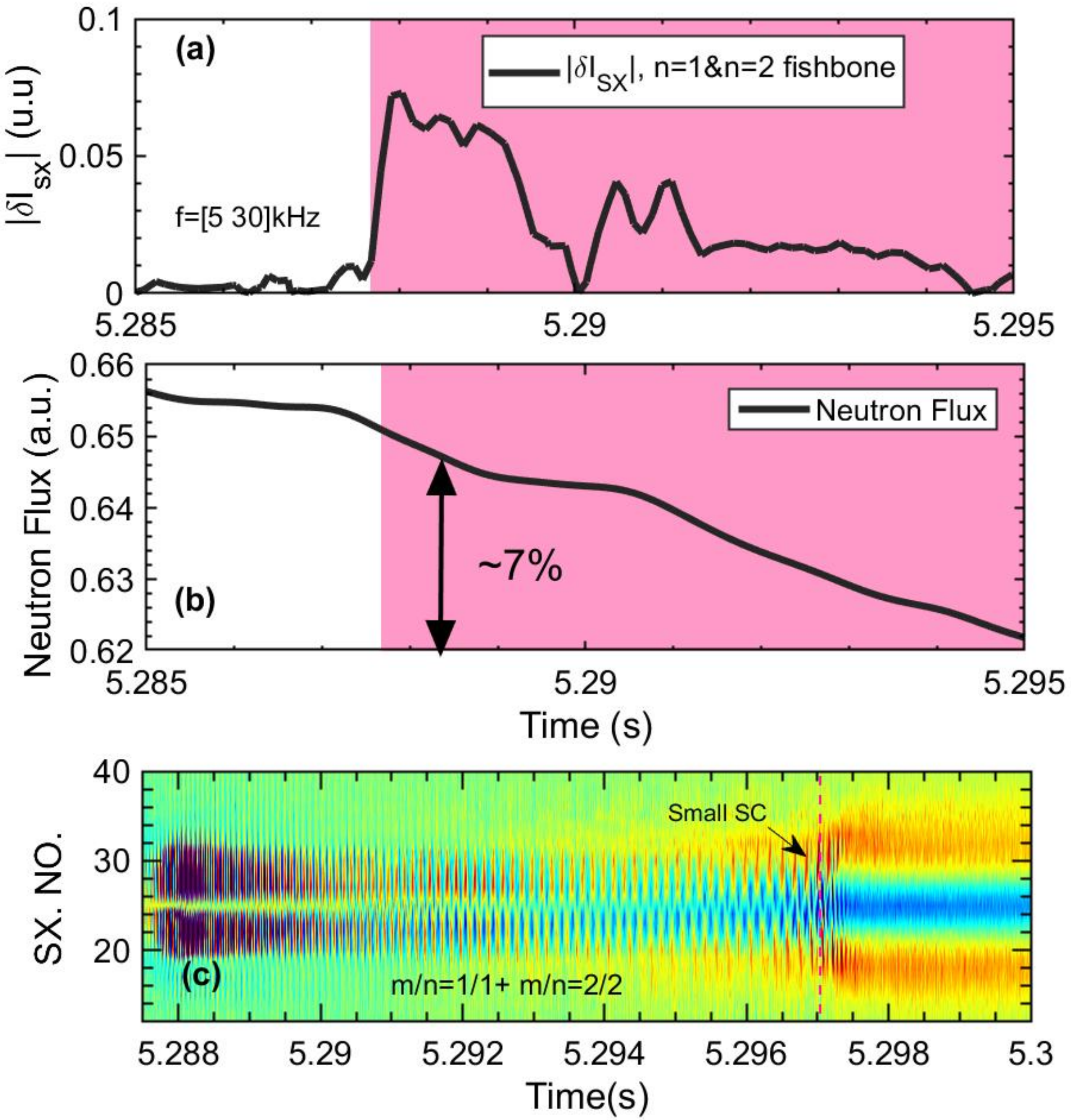
Neutron flux drops during fishbone evolution

- In EAST, neutron flux evolution is used to monitor the dynamics of energetic ions produced by NBI in the core region.
- A drop of neutron flux around 7% is observed during fishbones with m/n=1/1 and m/n=2/2 components.



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M3D-K model

resistive MHD+EP pressure coupling

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \nabla \cdot \mathbf{P}_h + \mathbf{J} \times \mathbf{B}$$

$$\mathbf{J} = \nabla \times \mathbf{B}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{dp}{dt} = -\gamma p \nabla \cdot \mathbf{v} + \rho \nabla \cdot \overleftrightarrow{\kappa} \cdot \nabla \frac{p}{\rho}$$

CGL form

$$\mathbf{P}_h = P_\perp \mathbf{I} + (P_\parallel - P_\perp)\mathbf{bb}$$

guiding center distribution

$$F = F(\mathbf{X}, v_\parallel, \mu) = \sum_i \delta(\mathbf{X} - \mathbf{X}_i)\delta(v_\parallel - v_{\parallel,i})\delta(\mu - \mu_i)$$

gyro-kinetic/drift kinetic equations

$$\frac{d\mathbf{X}}{dt} = \frac{1}{B^{\star\star}}[v_\parallel \mathbf{B}^\star - \mathbf{b}_0 \times (\langle \mathbf{E} \rangle - \frac{1}{e}\mu \nabla (B_0 + \langle \delta B \rangle))]$$

$$m\frac{dv_\parallel}{dt} = \frac{e}{B^{\star\star}}\mathbf{B}^\star \cdot [\langle \mathbf{E} \rangle - \frac{1}{e}\mu \nabla (B_0 + \langle \delta B \rangle)]$$

$$\mathbf{B}^\star = \mathbf{B}_0 + \langle \delta \mathbf{B} \rangle + \frac{m v_\parallel}{q} \nabla \times \mathbf{b}_0, \quad B^{\star\star} = \mathbf{B}^\star \cdot \mathbf{b}_0$$

G. Y. Fu et al., Phys. Plasmas 2006

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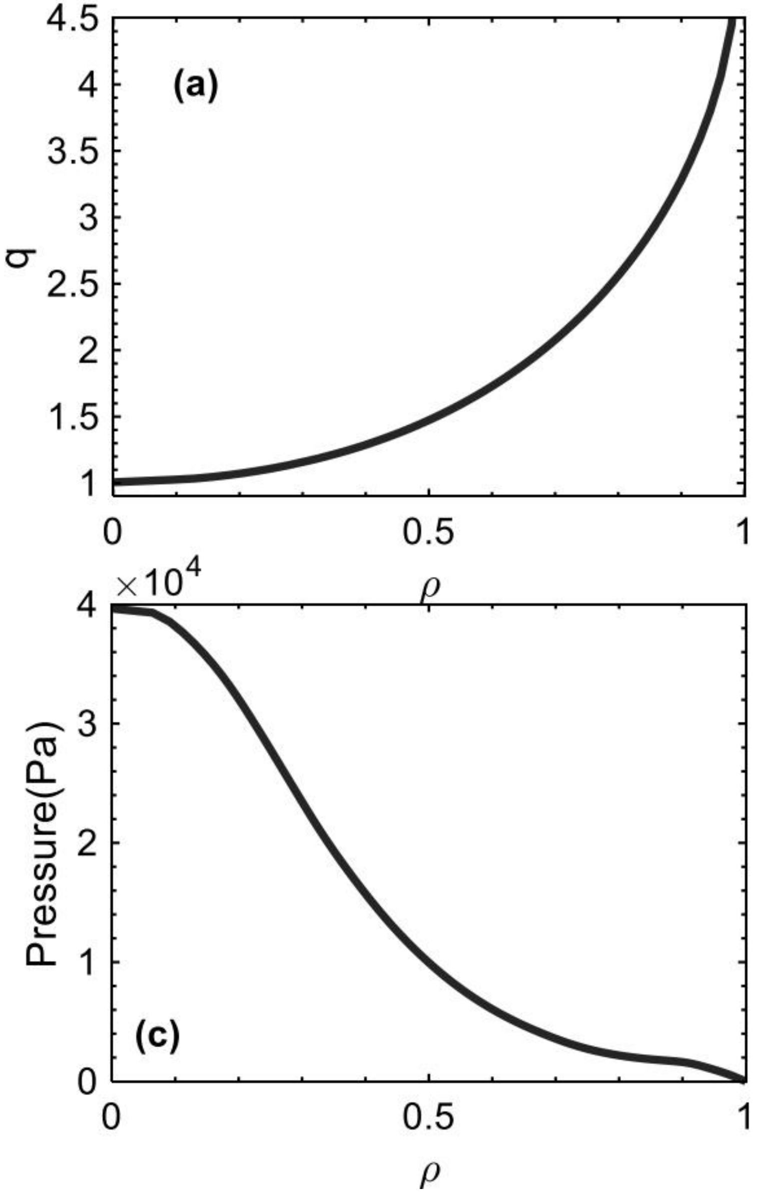
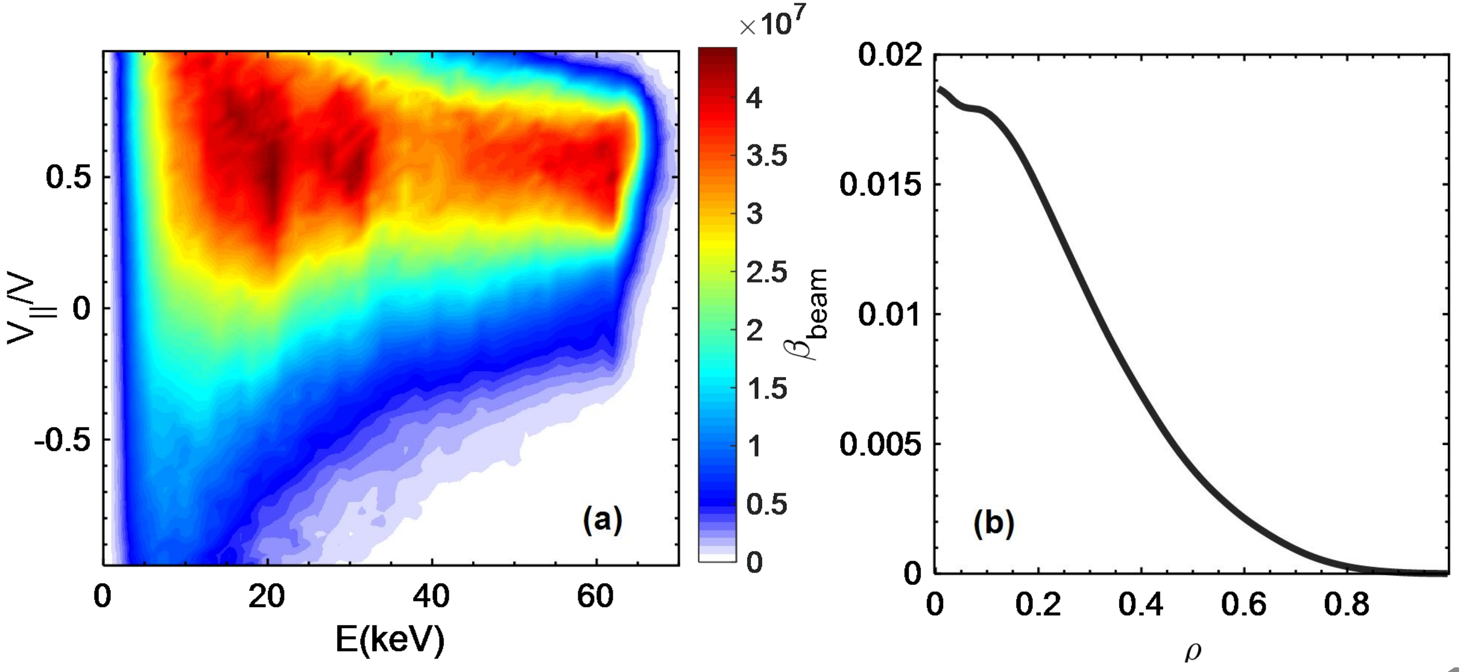
Initial profiles and parameters set up

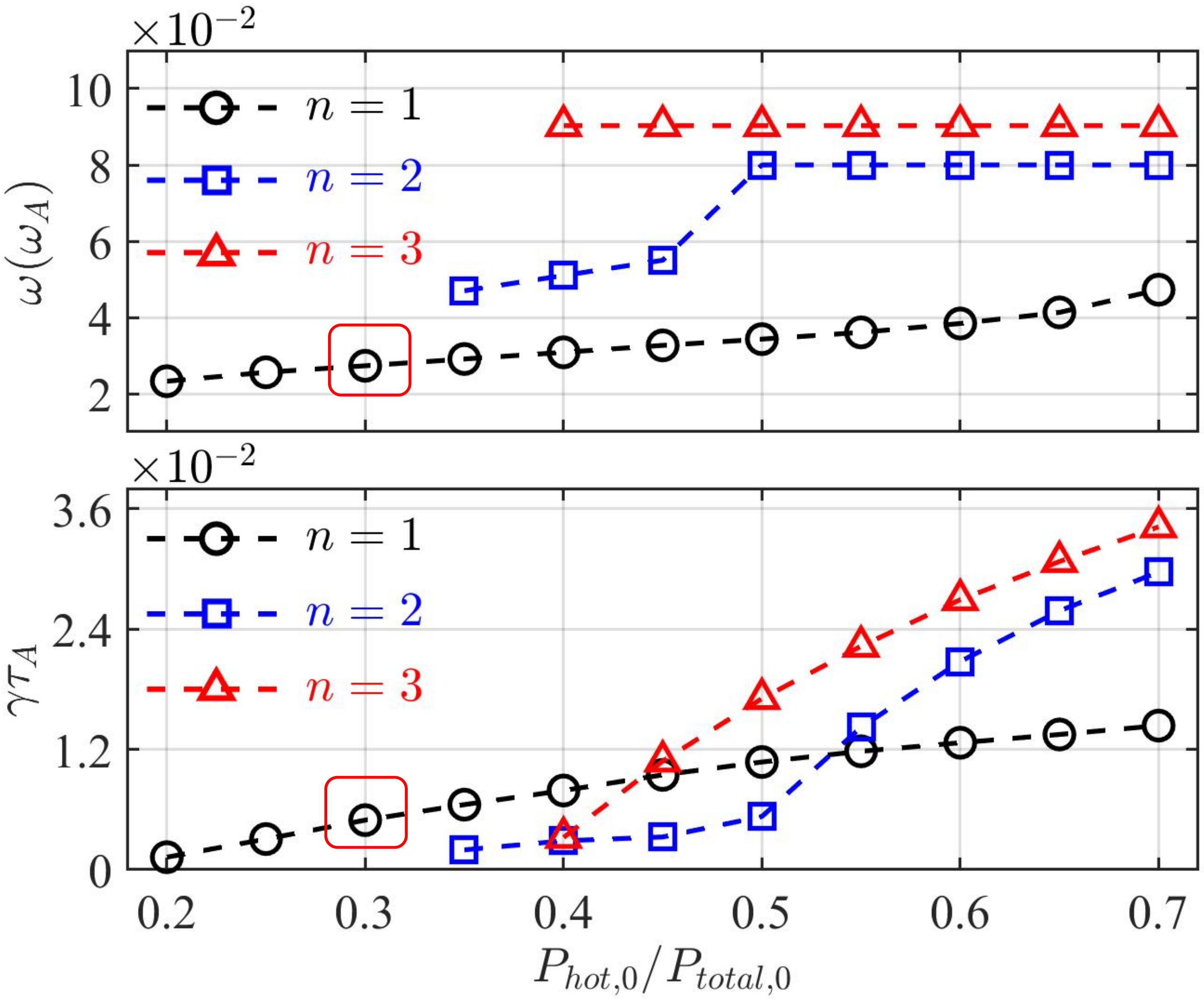


- **Initial profiles and parameters are chosen at t=5.288 s of #Shot 79024**



High order harmonis is excited when EP pressure increases

- **m/n=1/1 fishbone is exited when $P_{hot,0}/P_{total,0}>0.2$**
- **when EP pressure increases futher, n=2 and n=3 modes are driven unstable.**



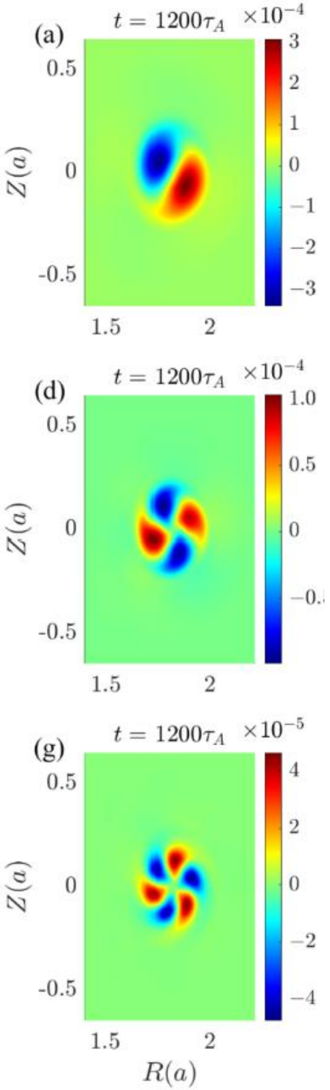
Precessional resonance is satisfied for n=1, 2, 3 modes

- $n\omega_\phi = \omega$ is satisfied for m/n=1/1, 2/2, 3/3 modes

m/n=1/1

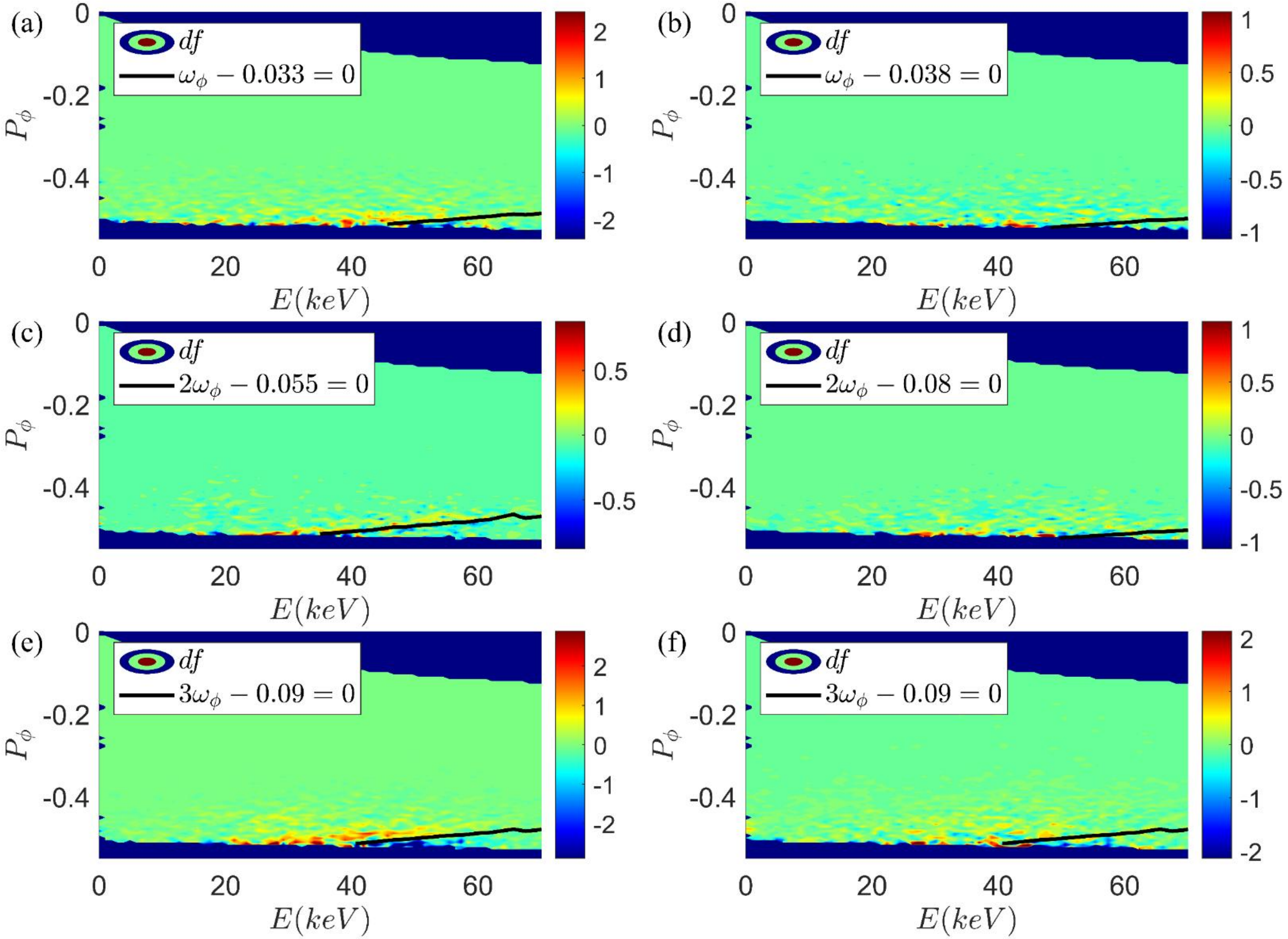
m/n=2/2

m/n=3/3



Phot/Ptotal=0.45

Phot/Ptotal=0.6



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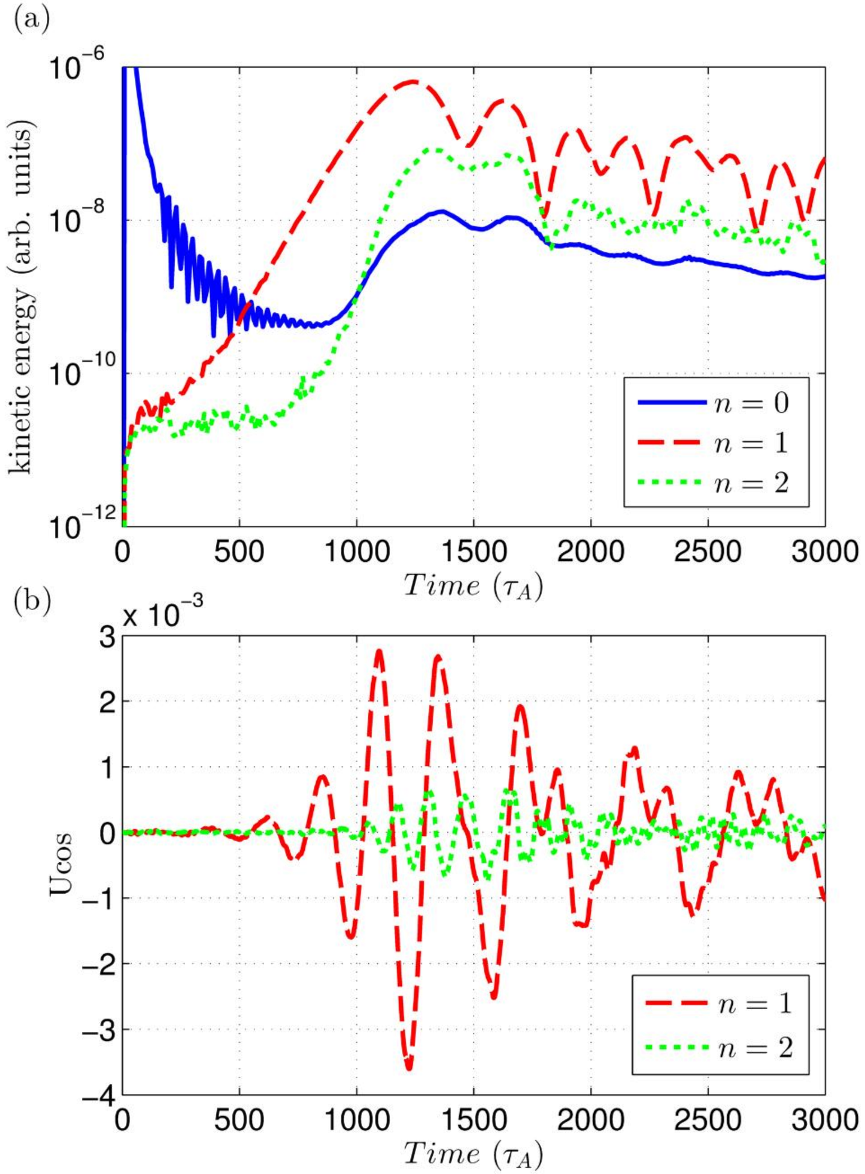
Kinetic energy evolution

- **Linear: n=1 mode is unstable, n=2, 3 modes are stable.**
- **Nonlinear evolution keeping from n=0 to n=2 shows that n=2 fishbone grows coupled to n=1 fishbone**
- **The m/n=2/2 fishbone is force-driven by the m/n=1/1 fishbone.**



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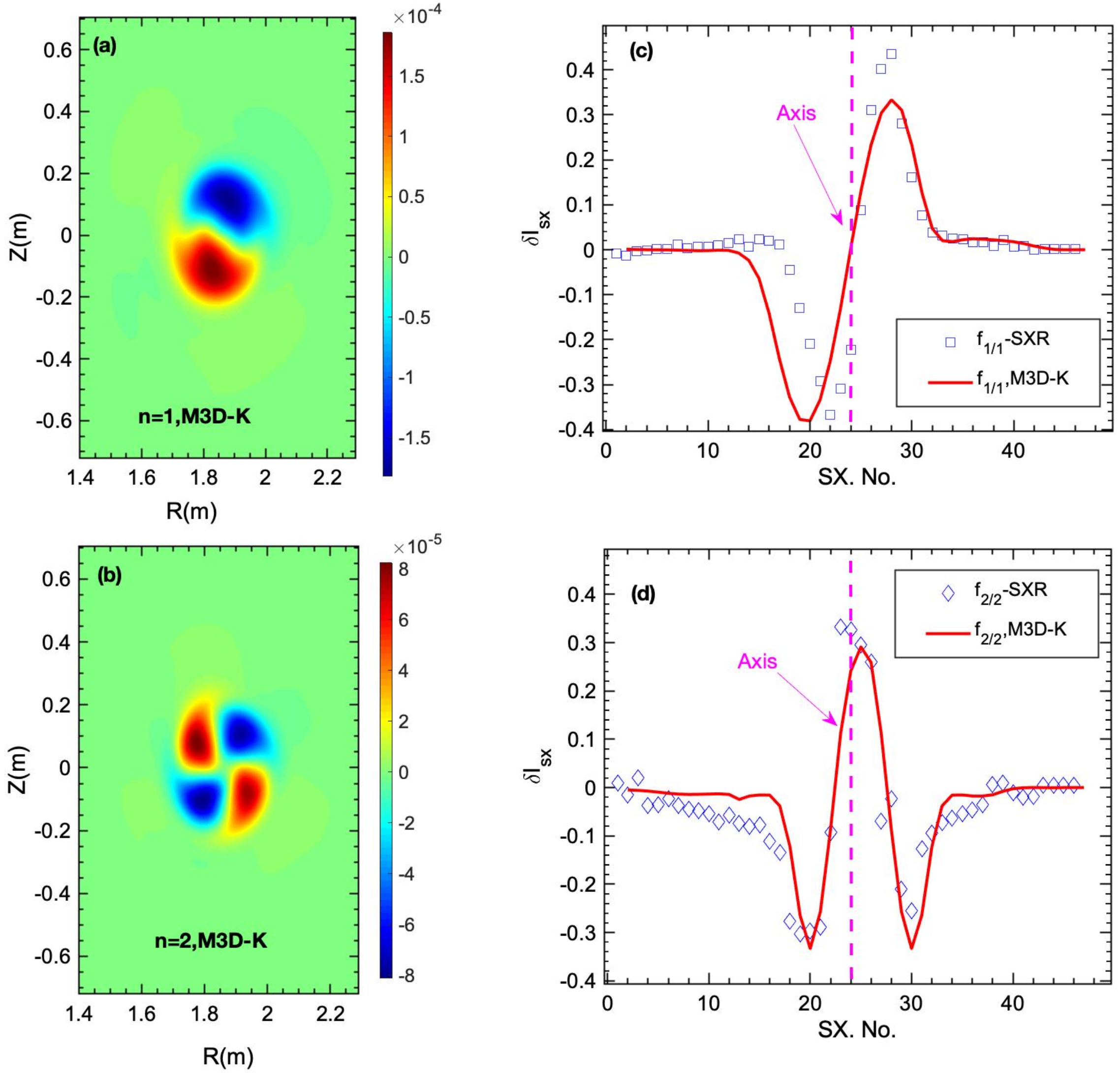
Mode structure in comparison with experiment

- The pressure perturbation structure of the m/n=1/1 and m/n=2/2 fishbones simulated by M3D-K code are shown in figures (a) and (b)
- Figures (c) and (d) show good agreements between simulation and experiment.



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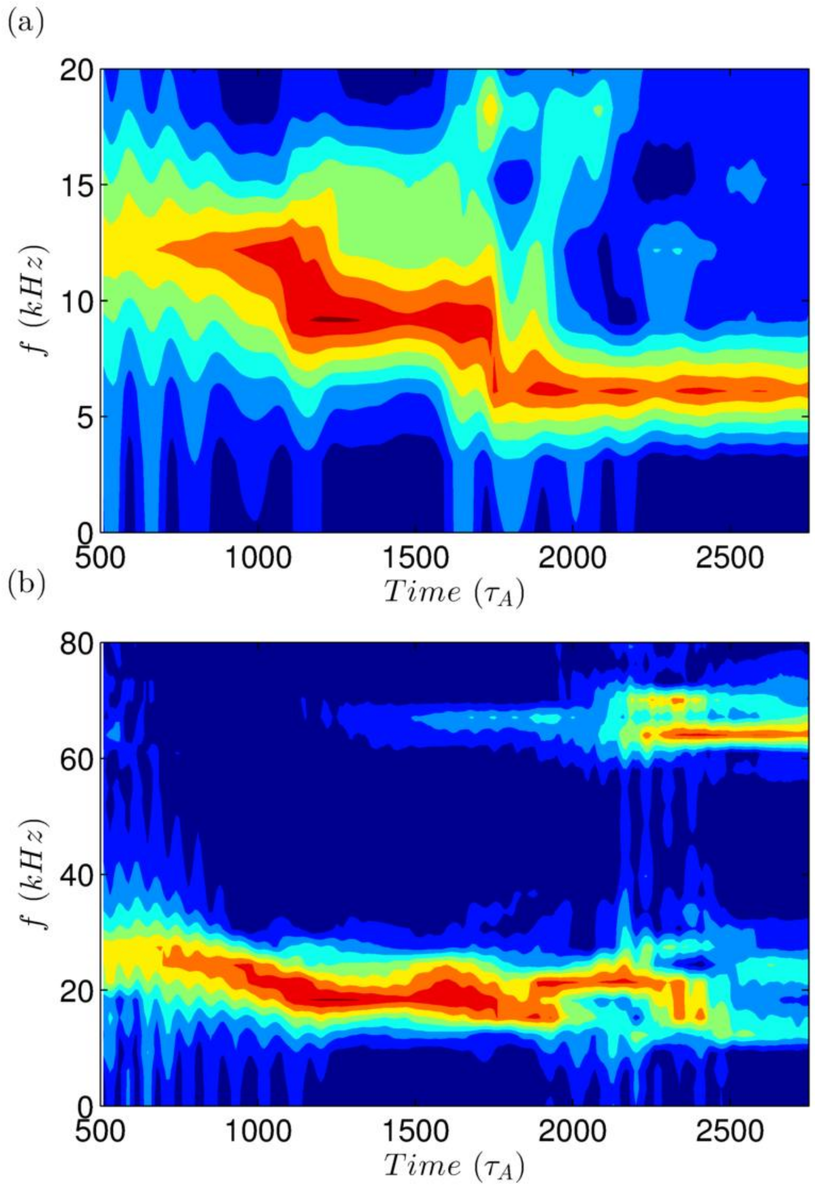
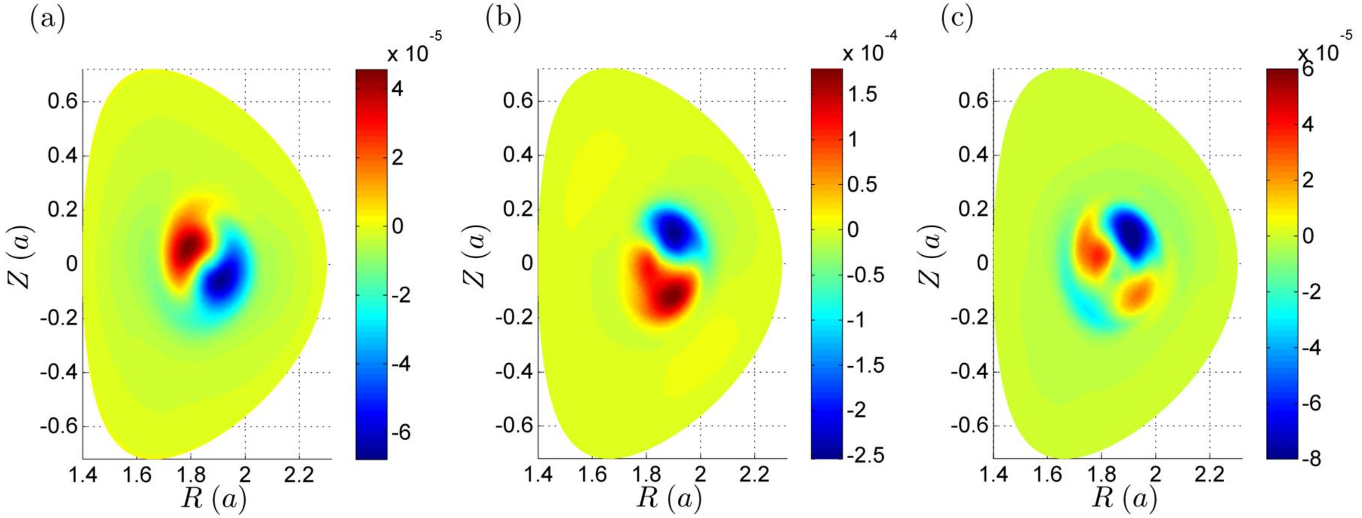
Mode frequency and structure evolution





- The frequency of the m/n=2/2 fishbone is around twice of the m/n=1/1 fishbone, and they chirp down together.
- At later nonlinear phase, the frequency of the m/n=2/2 fishbone chirps up and it transits to a high frequency BAE.

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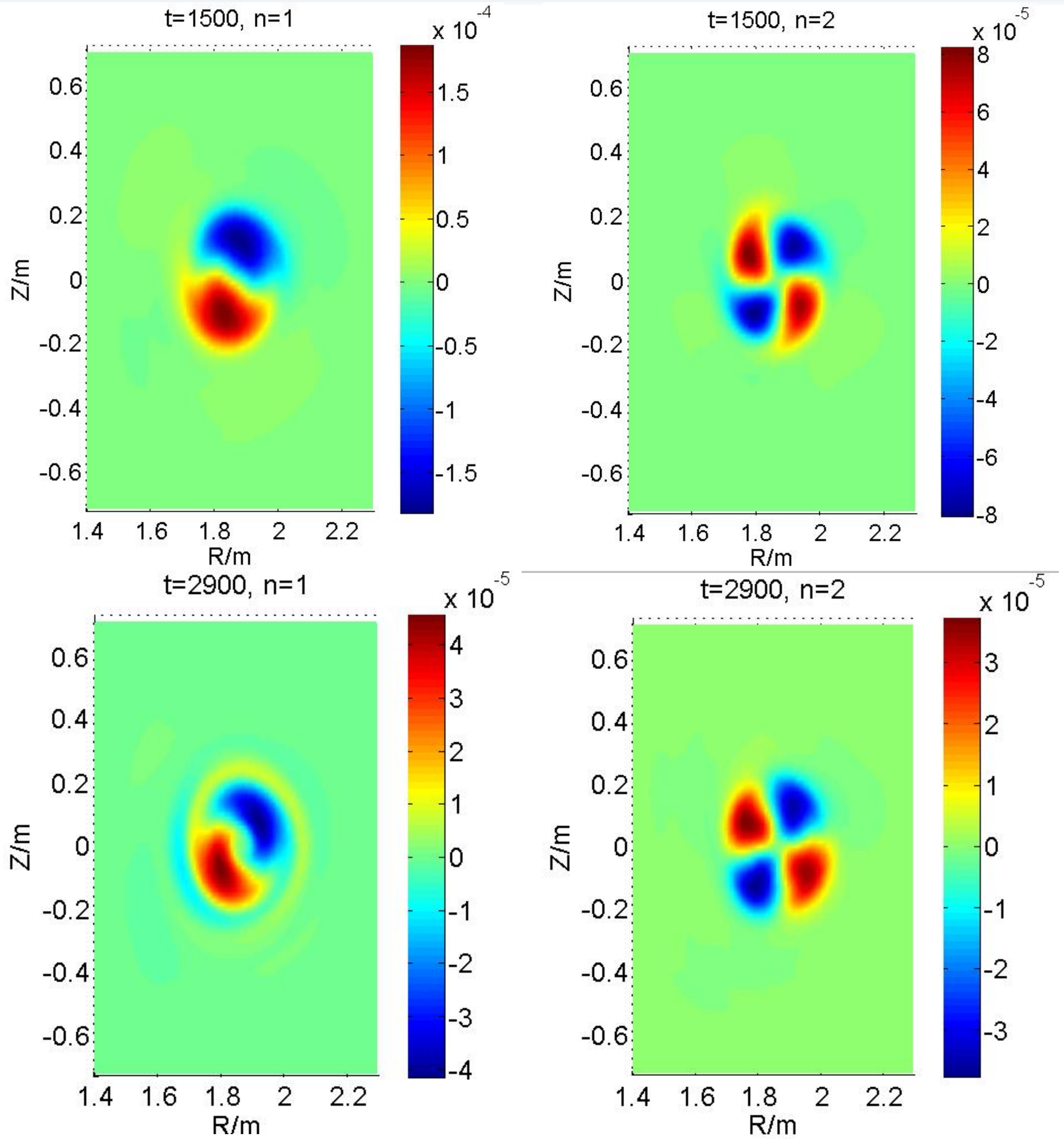
n=1 and n=2 mode structures

- n=1 mode: more twisted at t=2900
- n=2 mode: more twisted at t=1500
- High frequency n=2 mode at t=2900 is identified as BAE,
- t = 2900: $\omega_{n=2} = 0.138\omega_A$, consistent with BAE accumulation point in MHD limit $\omega_{BAE} = \sqrt{\gamma\beta}\omega_A = 0.140\omega_A$



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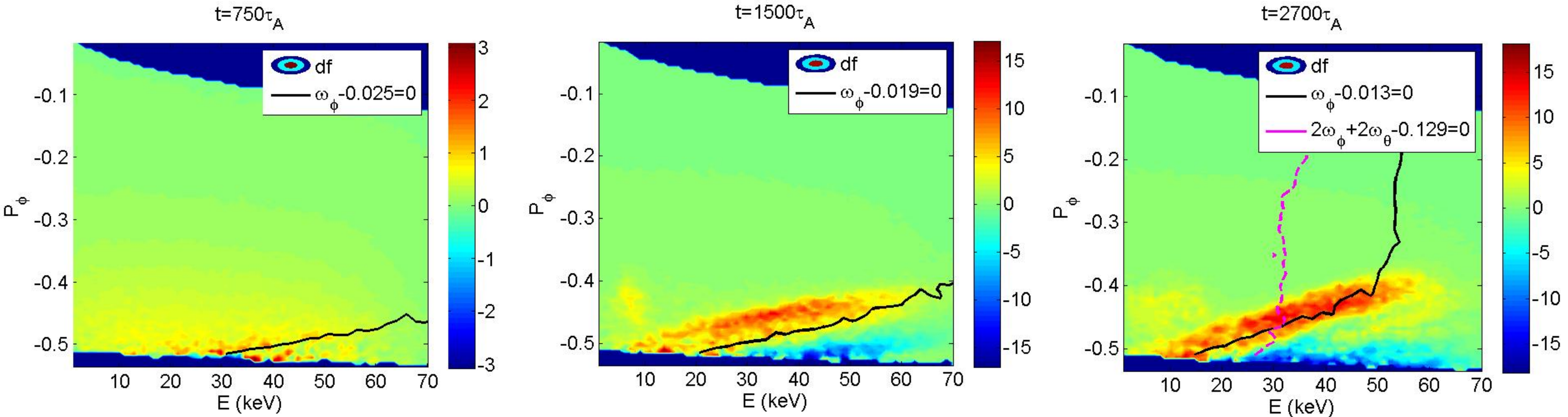
m/n=2/2 BAE is excited due to EP redistribution

- ✓ t=750τ_A: linear resonant condition for both *m*/*n*=2/2, 1/1 fishbones
- ✓ t=1500τ_A: early nonlinear phase, the frequency of *m*/*n*=2/2 fishbone chirps down together with *m*/*n*=1/1 fishbone
- ✓ t=2700τ_A: ***m*/*n*=2/2 BAE is excited nonlinearly due to EP transport in phase space**



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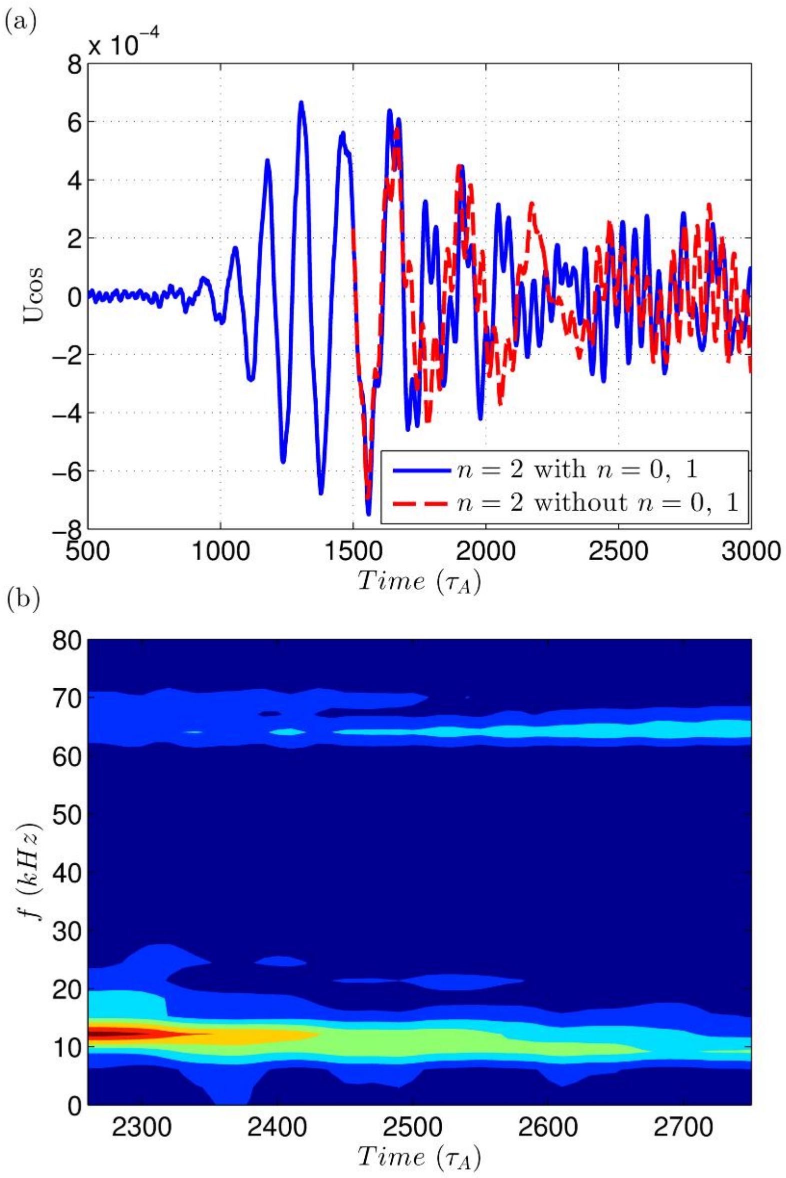
EP nonlinearity is dominant for fishbone saturation

- **The comparison between the amplitude of n=2 component with and without MHD nonlinearity shows that EP nonlinearity is dominant for the n=2 fishbone saturation and transition to BAE.**



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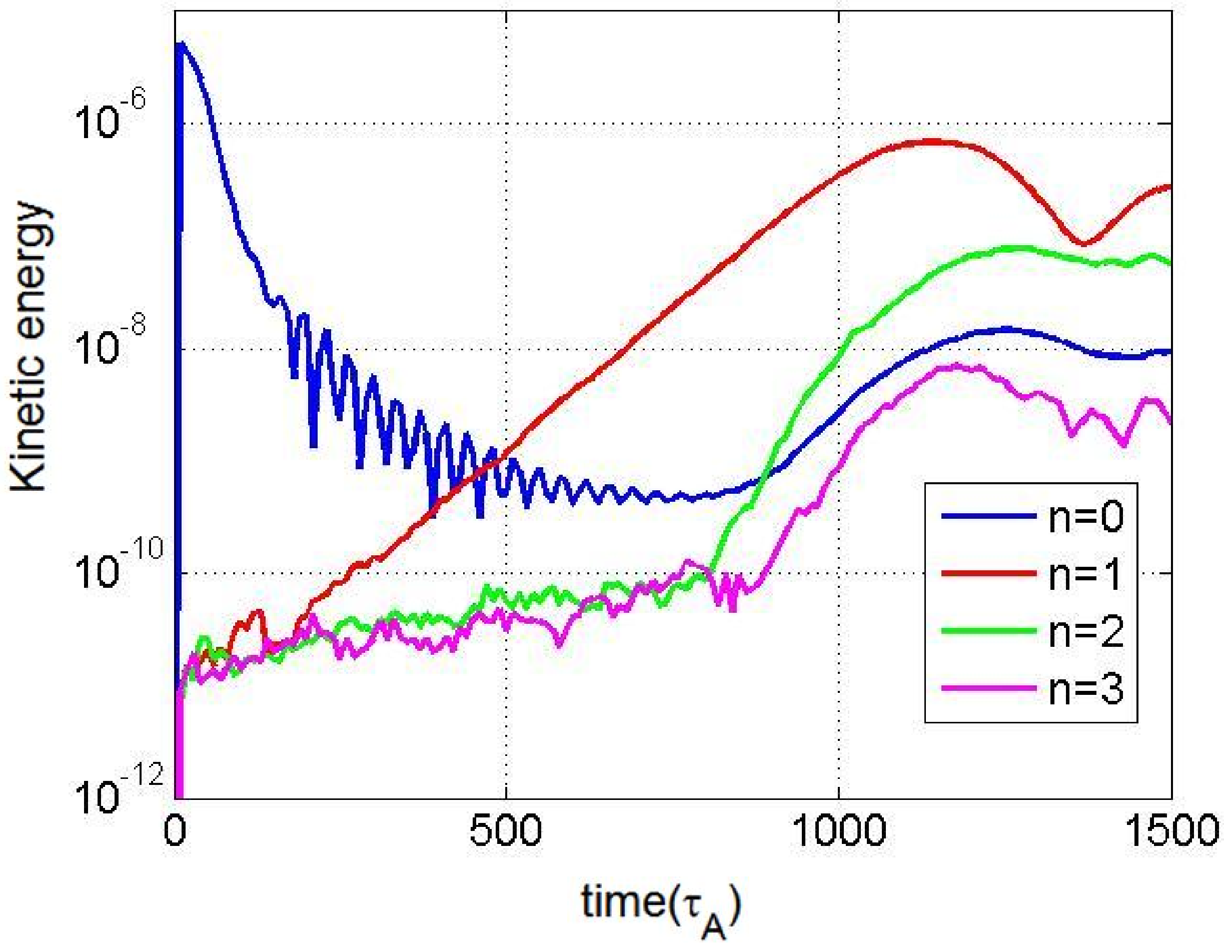
Simulation results keeping up to n=3 component



- **Kinetic energy of n=3 component is much smaller than n=1 and n=2 components, confirming that keeping up to n=2 mode in the simulation is enough, also consistent with experiment.**

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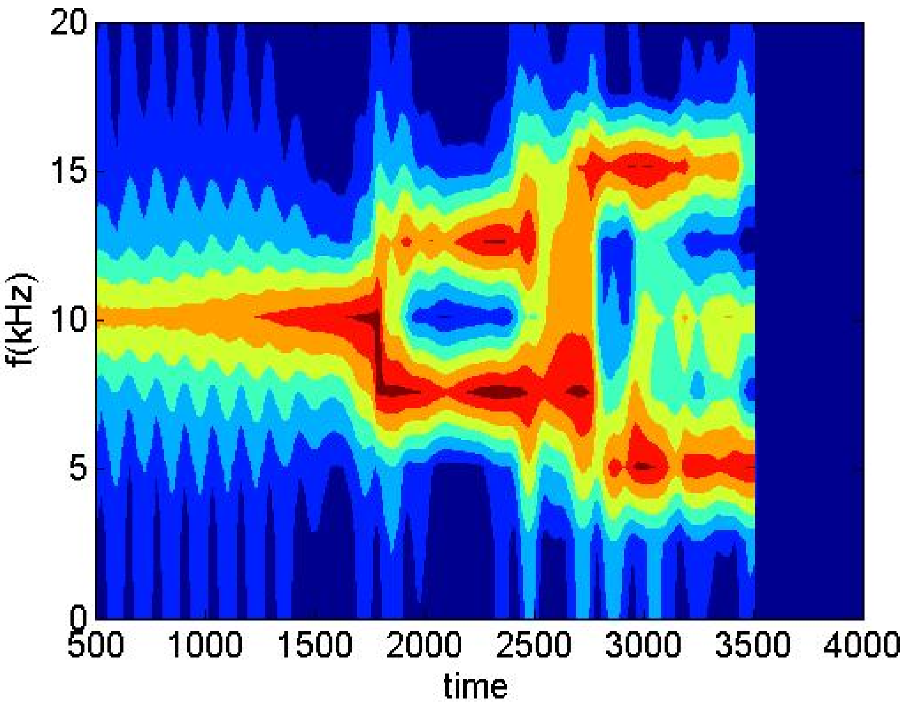
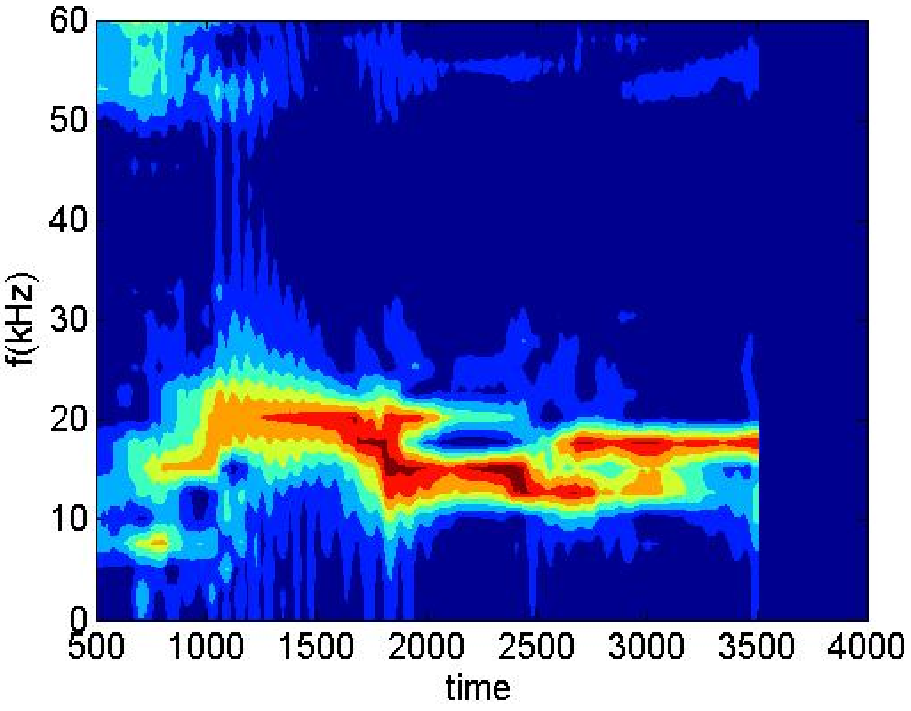
The frequency evolution changes with lower EP fraction

- Baseline case: $P_{hot,0}/P_{total,0}$=0.3, lower EP fraction case: $P_{hot,0}/P_{total,0}$=0.25
- The frequency of n=1 fishbone chirps up and down
- The n=2 fishbone does not transit to BAE.





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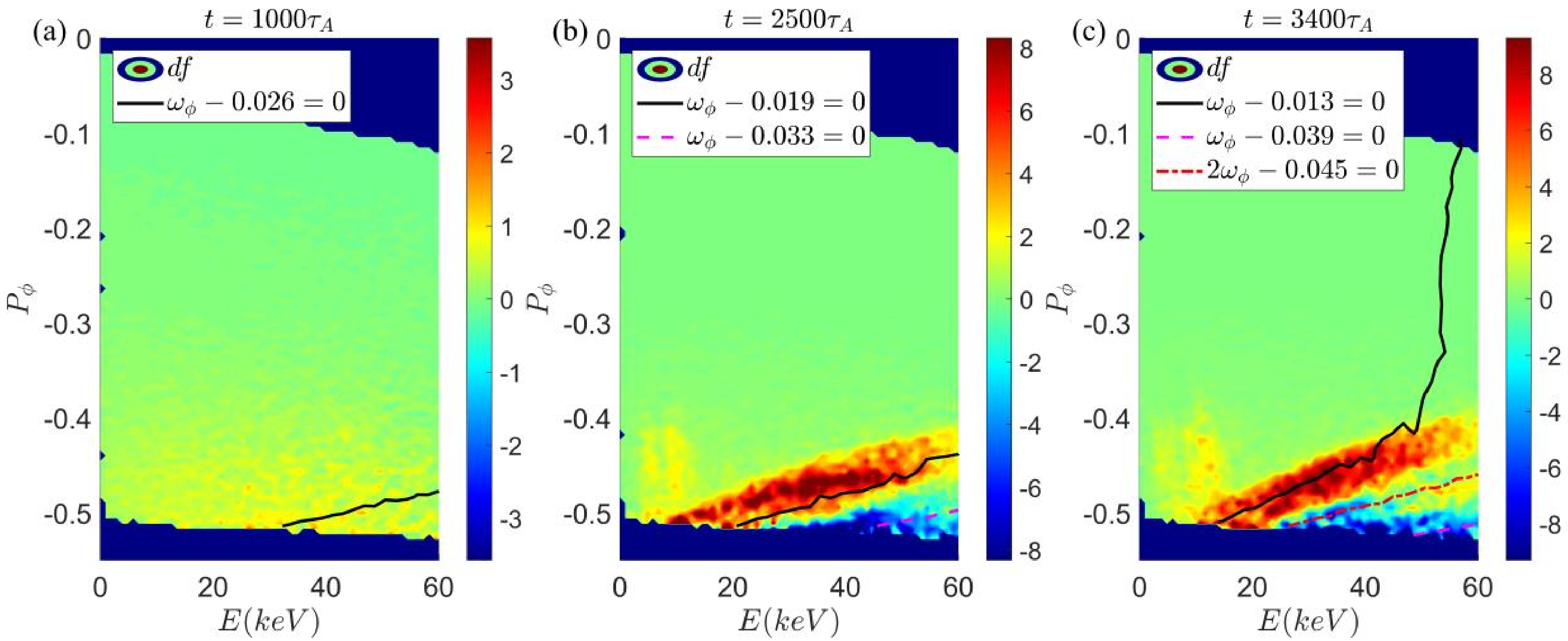
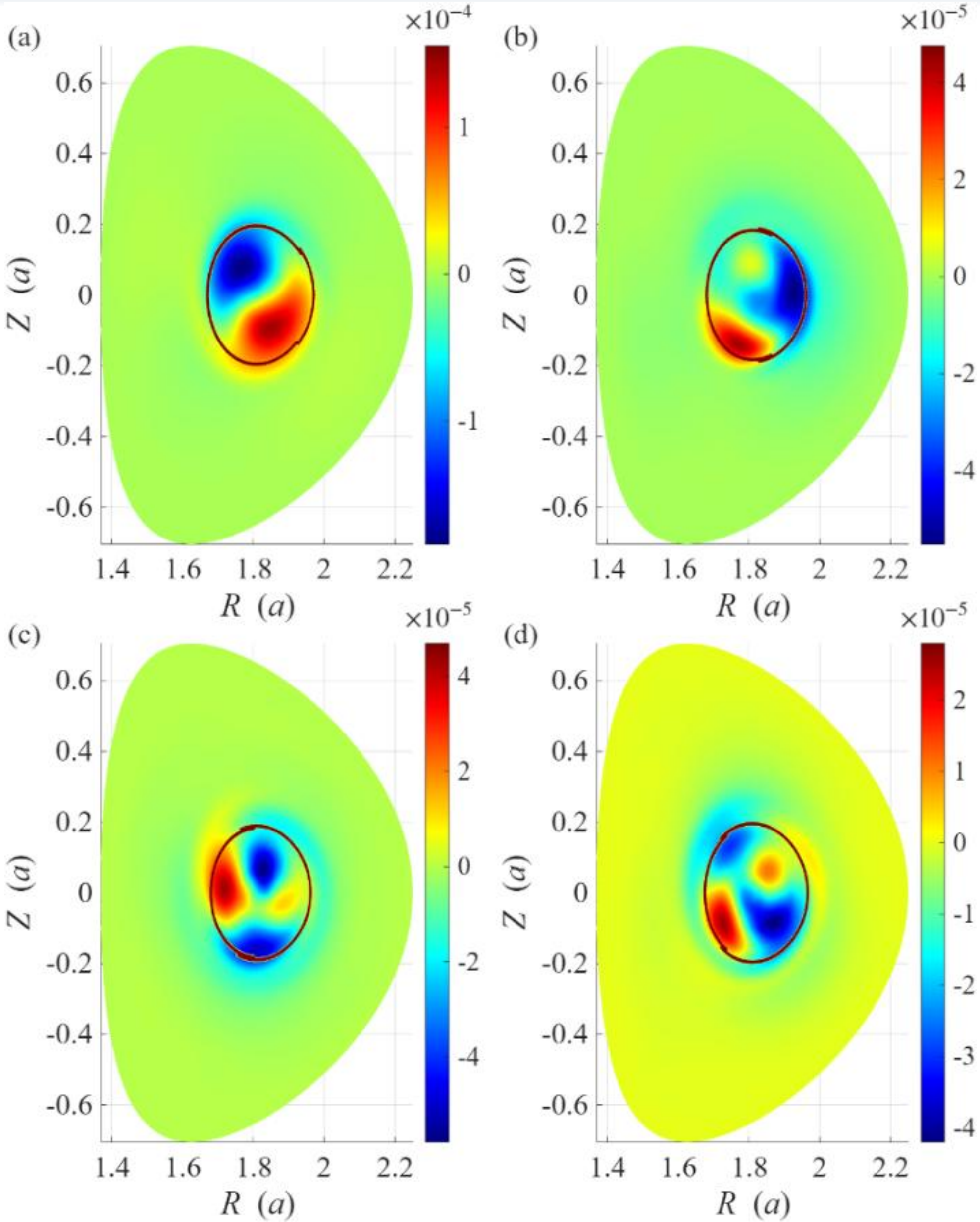
Resonance lines move with hole-clump structure

- The frequency of n=1 fishbone chirps up and down together with hole-clump structure formed in EP phase space
- Resonance lines move with EP hole-clump structure in phase space.



Nonlinear mode structure is affected by m/n=2/2 component

- **(a): Linear mode structure with m=n=1**
- **(b): early nonlinear phase: mode structure affected by m=n=2 component**
- **(c)-(d): fishbone with m=n=2 component becomes more obvious**



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Conclusion

The fishbones with n=1 and n=2 components on EAST have been simulated by M3D-K code.

- **n=2 mode is linearly stable, but nonlinearly grows coupled with n=1 mode.**
- **The m/n = 2/2 fishbone frequency is almost twice of the m/n = 1/1 fishbone, and both fishbone frequencies chirp down together.**
- **The n=2 fishbone transits to a high frequency BAE at later nonlinear phase.**
- **EP nonlinearity is dominant for n=2 mode saturation and transition to BAE.**

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Thank you for your attention!