



中国科学技术大学

University of Science and Technology of China

Fine Reversed Structure of Zonal Flow Driven by Fishbone in Tokamak Plasmas

Yuehao Ma¹

Joint work with Liutian Gao¹, Huishan Cai¹, AhDi Liu¹

Bin Zhang², Ming Xu², Haiqing Liu², Liqing Xu², Chu Zhou¹, Feifei Long¹,
Mingyuan Wang¹, Xiaoming Zhong², Jinlin Xie¹, Ge Zhuang¹, and the EAST team

¹*University of Science and Technology of China, Hefei*

²*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei*

2026/9/29

Outline

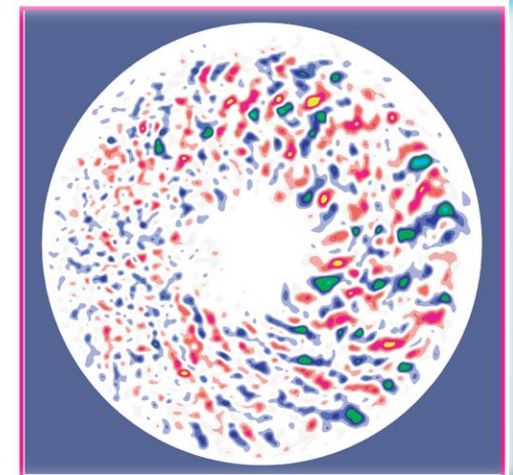
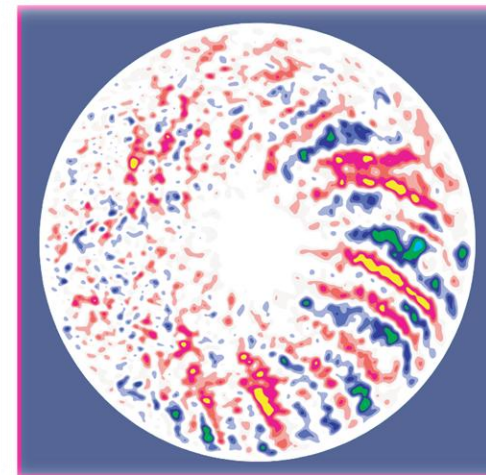
- ◆ **Background and Motivation**
- ◆ **Experimental results**
- ◆ **Fishbone simulation results**
- ◆ **Conclusions**

Outline

- ◆ **Background and Motivation**
- ◆ Experimental results
- ◆ Fishbone simulation results
- ◆ Conclusions

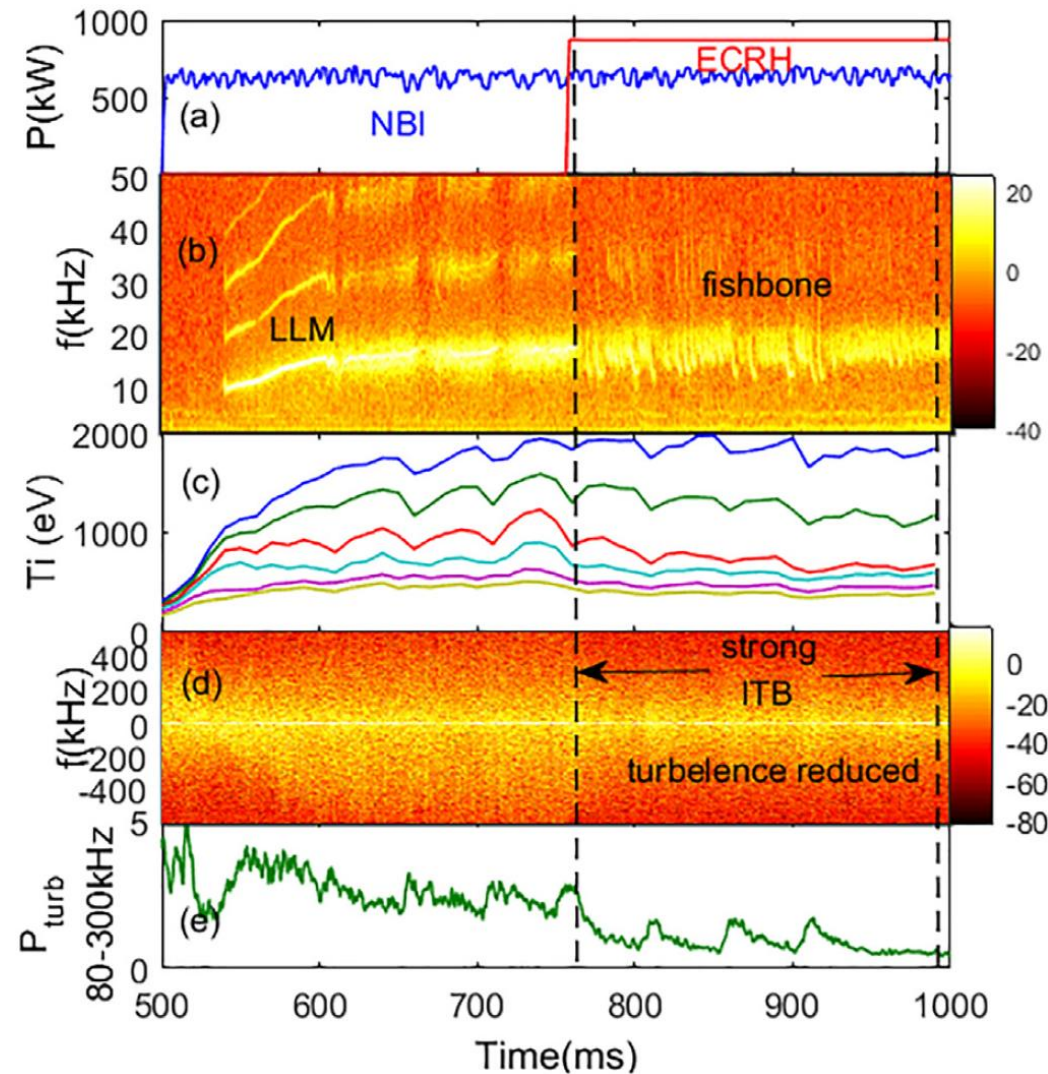
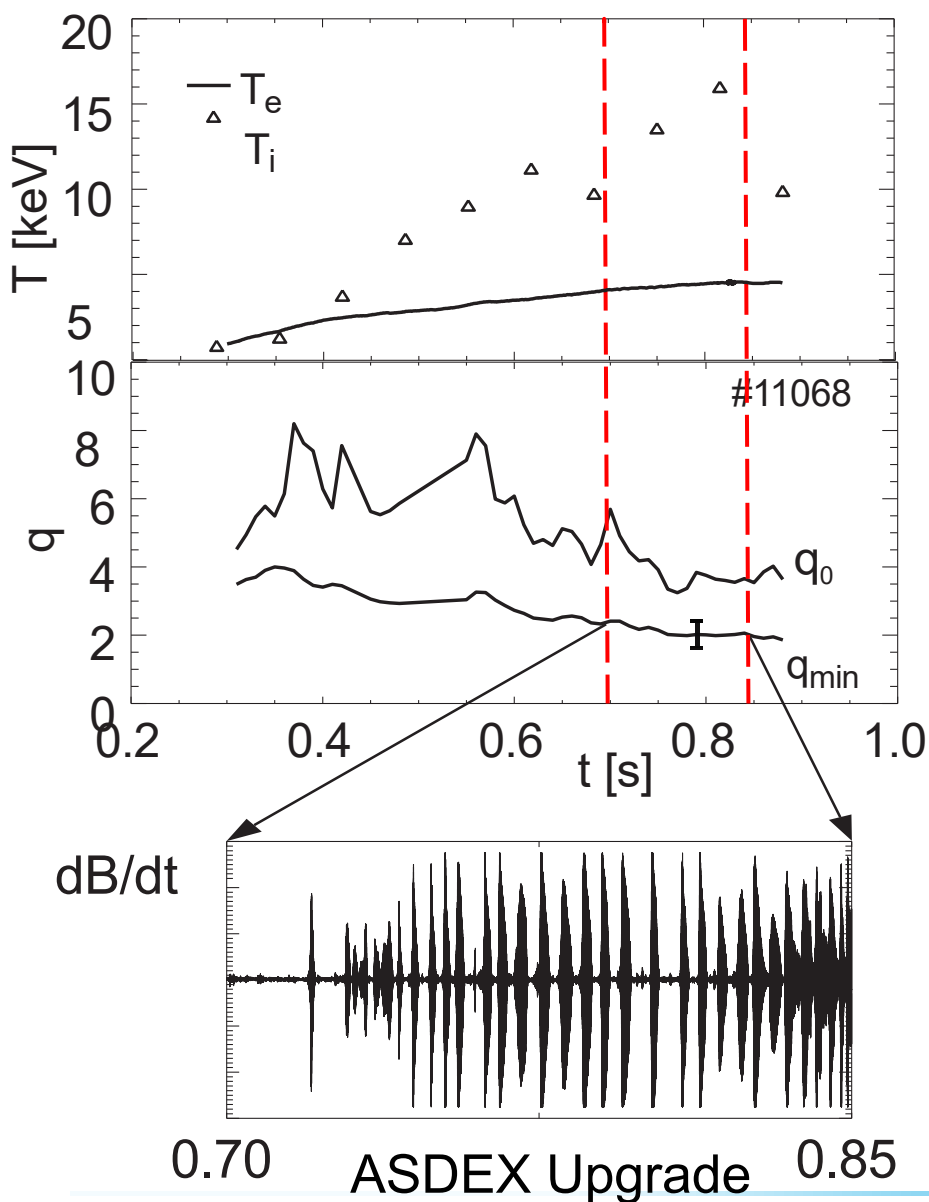
Background and Motivation

- ◆ Symmetric bandlike sheared flow are ubiquitous phenomena in the Universe
 - banded structures on Jupiter, the terrestrial atmospheric jet stream...
 - These flow can stretch and tilt turbulent eddies, and reduce coherence length
- ◆ Sheared flow in magnetically confined plasmas
 - generated by the equilibrium radial electric field, or by turbulence itself as zonal flow
 - $\mathbf{E} \times \mathbf{B}$ flow is responsible for suppress turbulence, and improve confinement



Biglari, Diamond & Terry, Phys. Fluids B (1990); Terry, Rev. Mod. Phys. (2000); Lin et al., Science(1998); Burrell, Phys. Plasmas (1997)

Correlation between fishbone and confinement enhancement



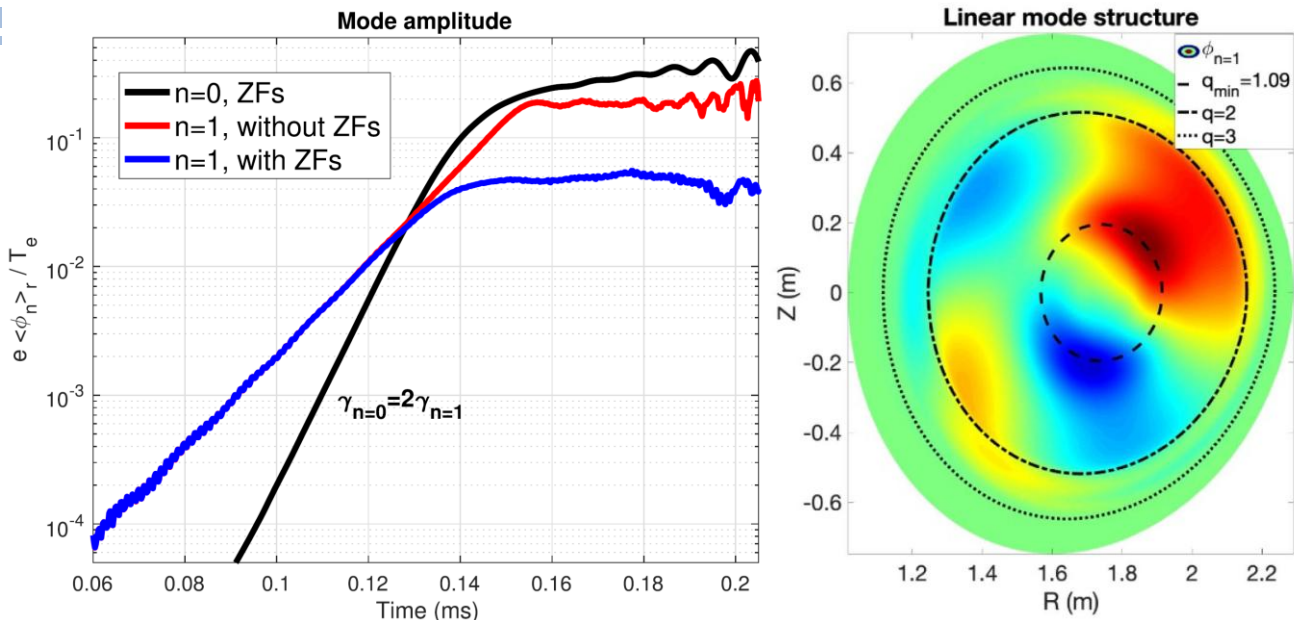
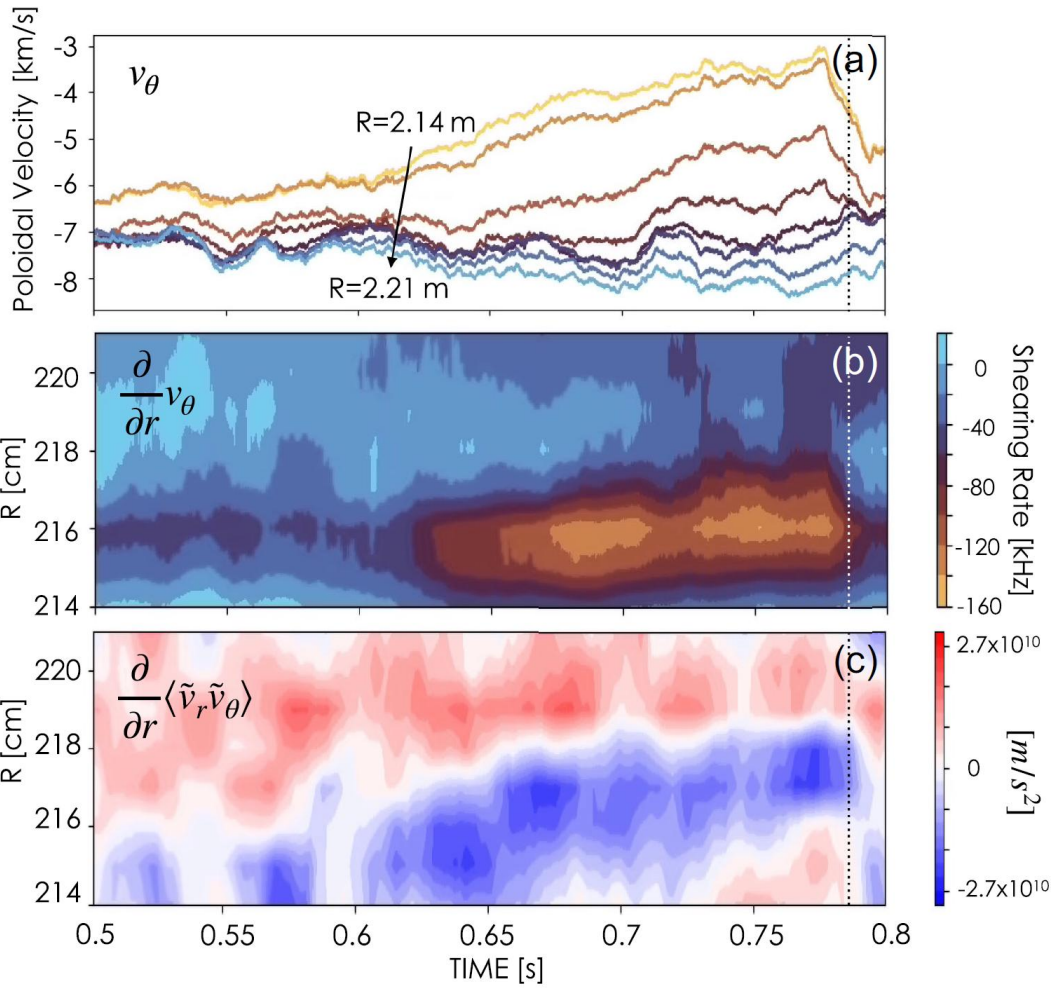
ASDEX Upgrade, the formation of ion ITB was observed when the fishbone oscillation.

In HL-2A, the core turbulence is strongly reduced after the fishbone burst.

HL-2A

McGuire et al., PRL (1983); Chen et al., PRL (1984); Coppi & Porcelli, PRL (1986); Gunter et al., NF (2001); Deng Wei, et al. PoP (2022); Zhang et al., NF (2022)

Possible mechanism for the correlation



- Simulations have also shown that fishbone can generate strong zonal flow, which play an important role in fishbone saturation. However, direct experimental evidence is still limited.
- Observed fishbone-driven zonal flow with a fine reversed radial structure. Investigated its generation mechanism and radial structure using GTC.

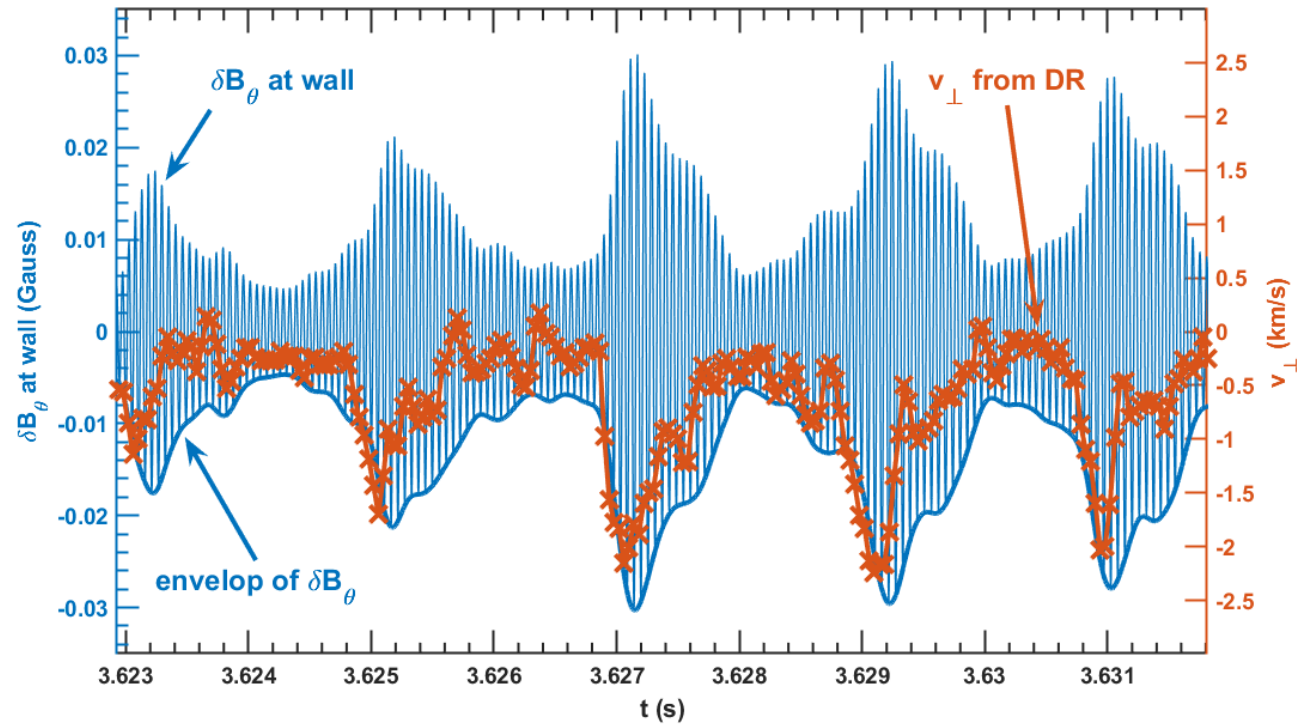
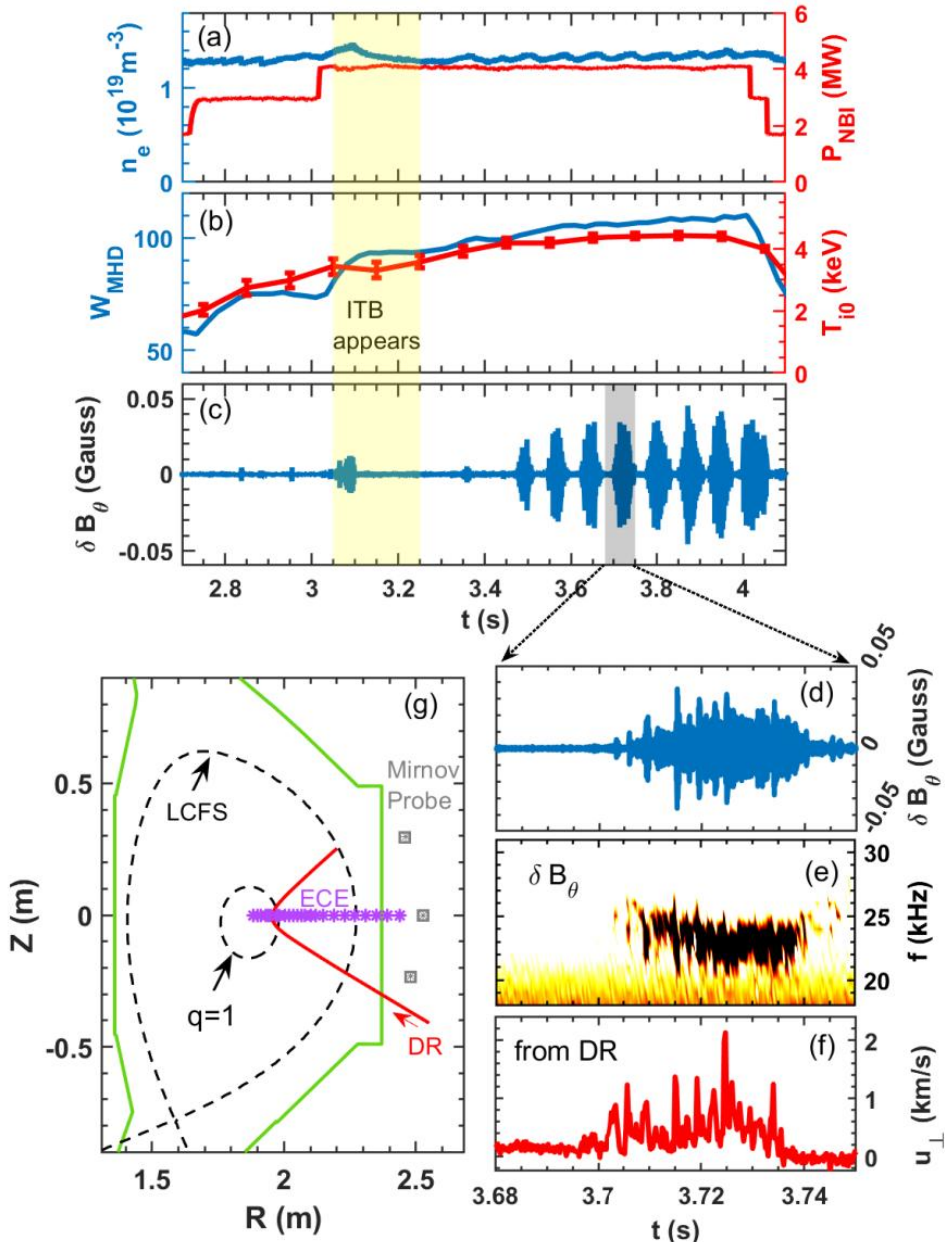
- TAE-driven shear flow suppresses microturbulence in DIII-D.
- $AE \rightarrow \begin{cases} \text{Zonal flow} \\ \text{Zonal current} \end{cases} \rightarrow \begin{cases} E \times B \text{ flow shear} \\ \text{magnetic structure} \end{cases} \rightarrow \text{turbulence regulation.}$

Chen & Zonca, PRL (2012); Qiu et al., PoP (2016); Qiu et al., NF (2017); Liu et al., PRL (2022); Brochard et al., PRL (2024); Du et al., PRL (2025); Heidbrink et al., PRL (2026).

Outline

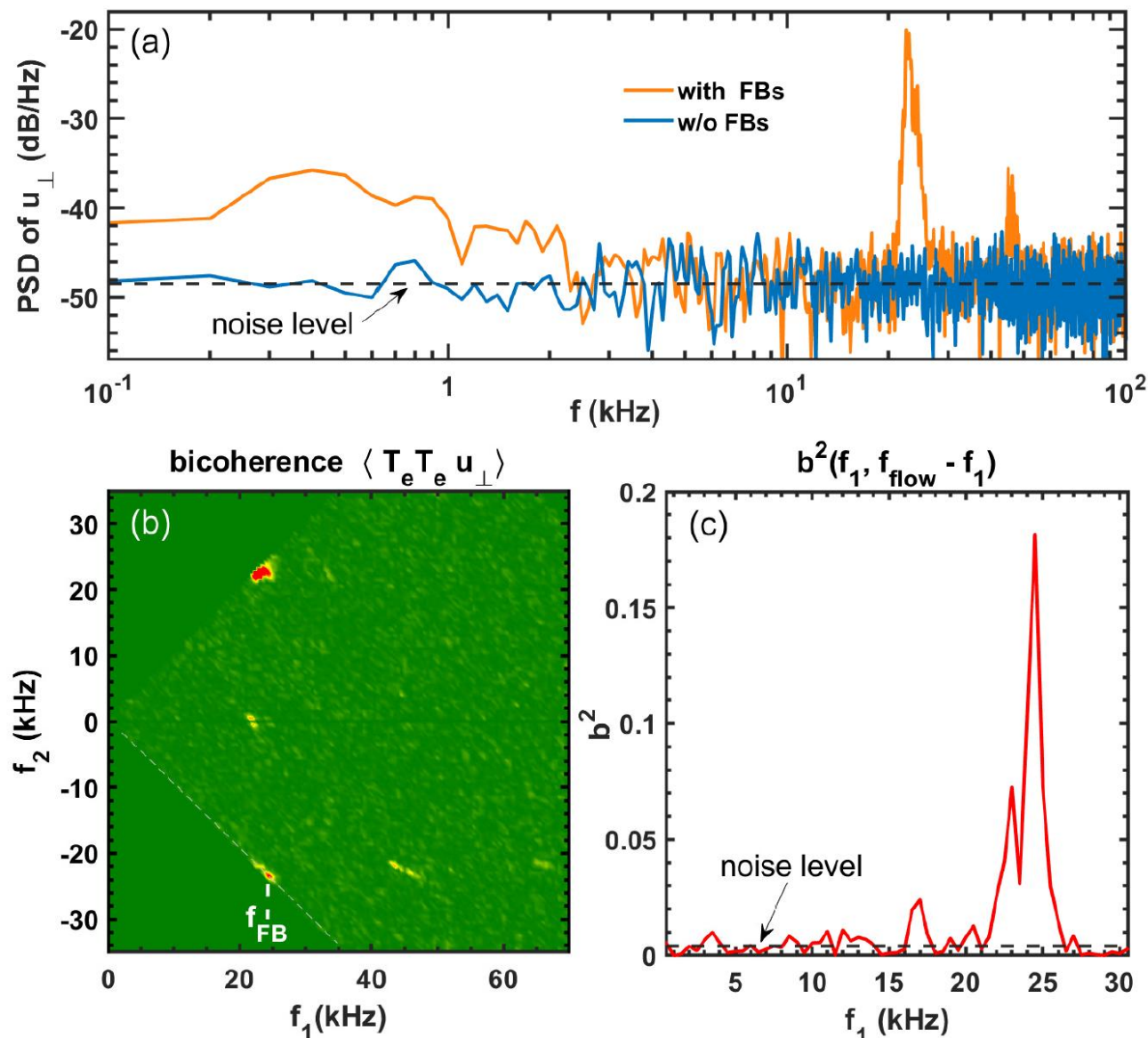
- ◆ Background and Motivation
- ◆ **Experimental results**
- ◆ Fishbone simulation results
- ◆ Conclusions

Correlation between fishbone and $E \times B$ flow



- Low density plasmas, NBI dominant heating #133556
- Fishbones burst periodically after the formation of ITB
- Doppler reflectometry (DR) is used to measure the $E \times B$ velocity within the $q = 1$ resonant surface
- $E \times B$ velocity show clear coincidence with fishbone bursts

Bicoherence analysis for fishbone and flow

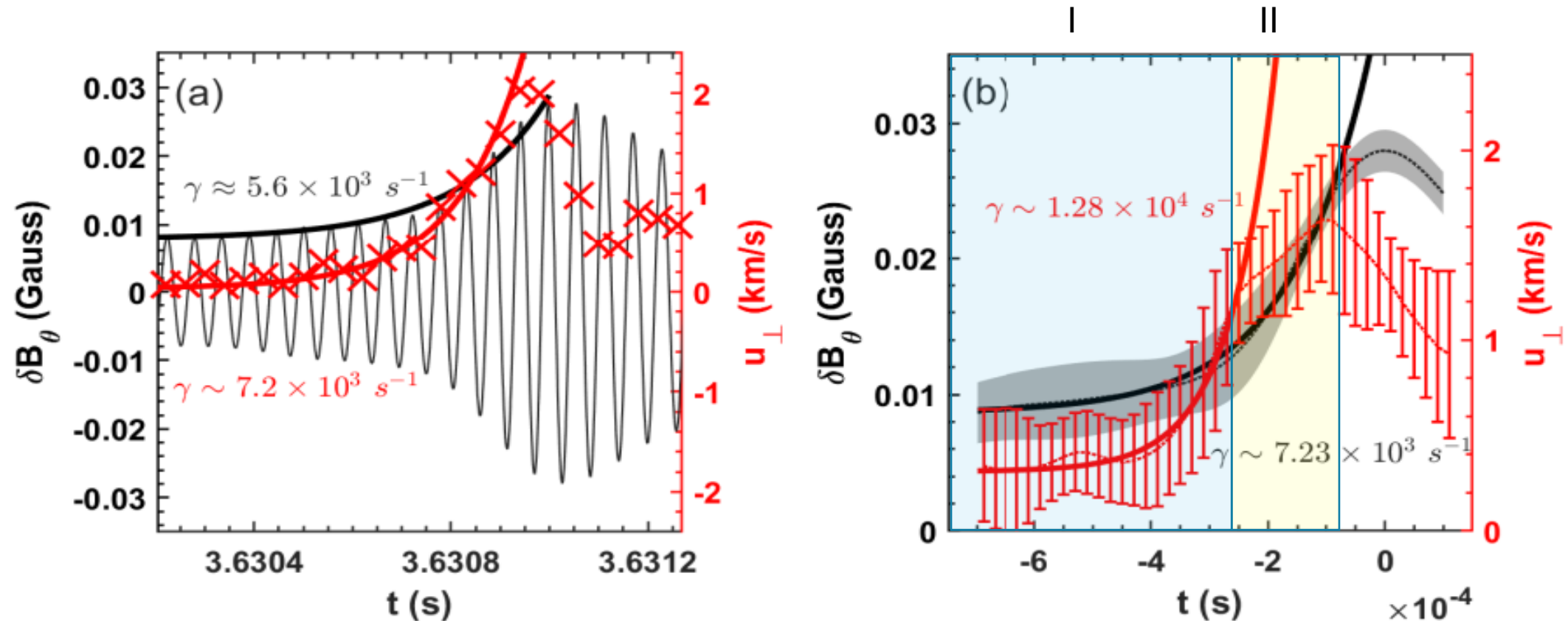


- The power spectrum shows that a strong low-frequency flow appears during fishbone bursts.
- The bicoherence spectrum shows a clear phase-coherent coupling, and the corresponding peak is located around the fishbone frequency.
- These indicate that the low-frequency flow is generated through nonlinear self-coupling of the fishbone mode.

$$b^2(f_1, f_2) = \frac{|\langle F_1(f_1)F_2(f_2)F_3^*(f_1 + f_2) \rangle|^2}{\langle |F_1(f_1)F_2(f_2)|^2 \rangle \langle |F_3^*(f_1 + f_2)|^2 \rangle},$$

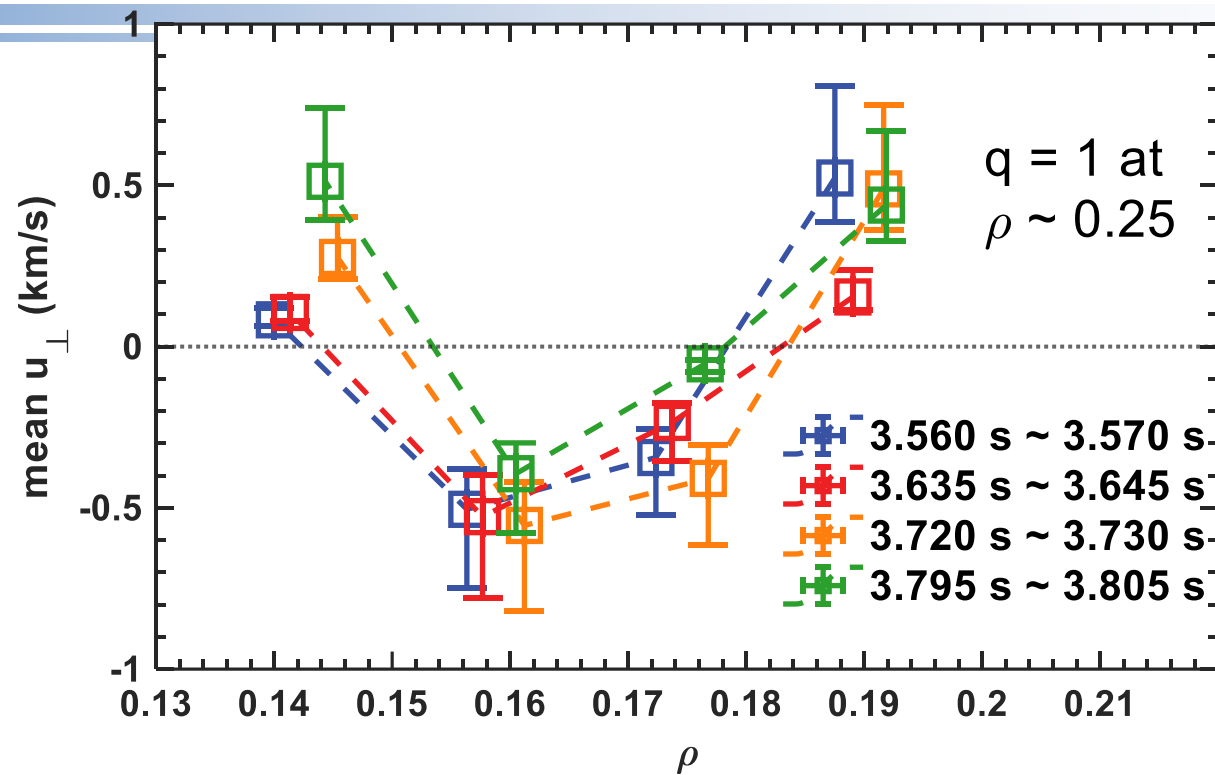
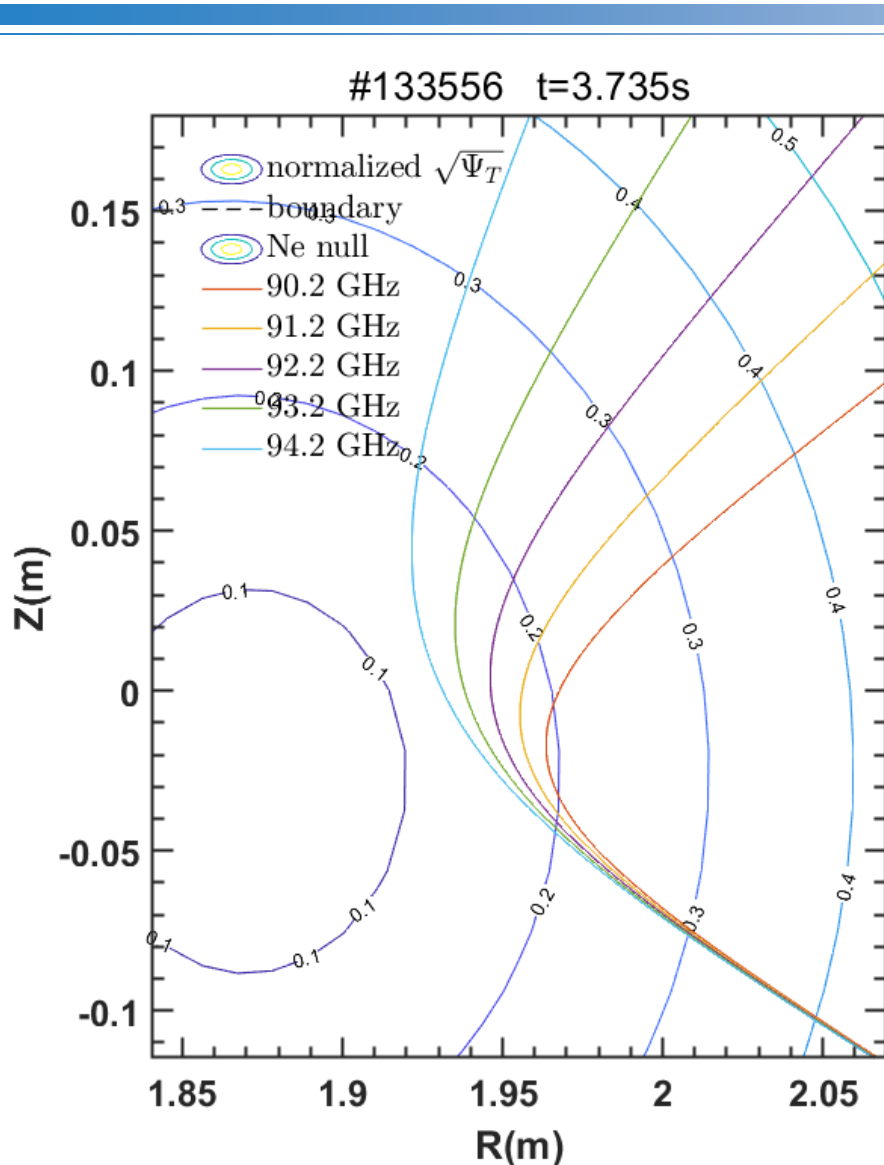
$b_2(f_1, f_2)$ represents a phase-matched relationship between f_1 and f_2 to generate the third frequency $f_1 + f_2$, representing the three-wave nonlinear mode coupling between fluctuations of f_1 and f_2 .

Time evolution of zonal flow in fishbone bursts



- The generation of zonal flow shows a clear two-stage behavior during the fishbone bursts.
- In the early stage, the zonal flow grows faster than the fishbone mode. In the later stage, the zonal flow reaches its peak earlier than the fishbone mode.
- This behavior is more consistent with a beat-driven process of the fishbone, which can generate zonal flow, rather than the energetic-particle expulsion mechanism.

Reversed zonal flow structure within the $q=1$ resonant surface

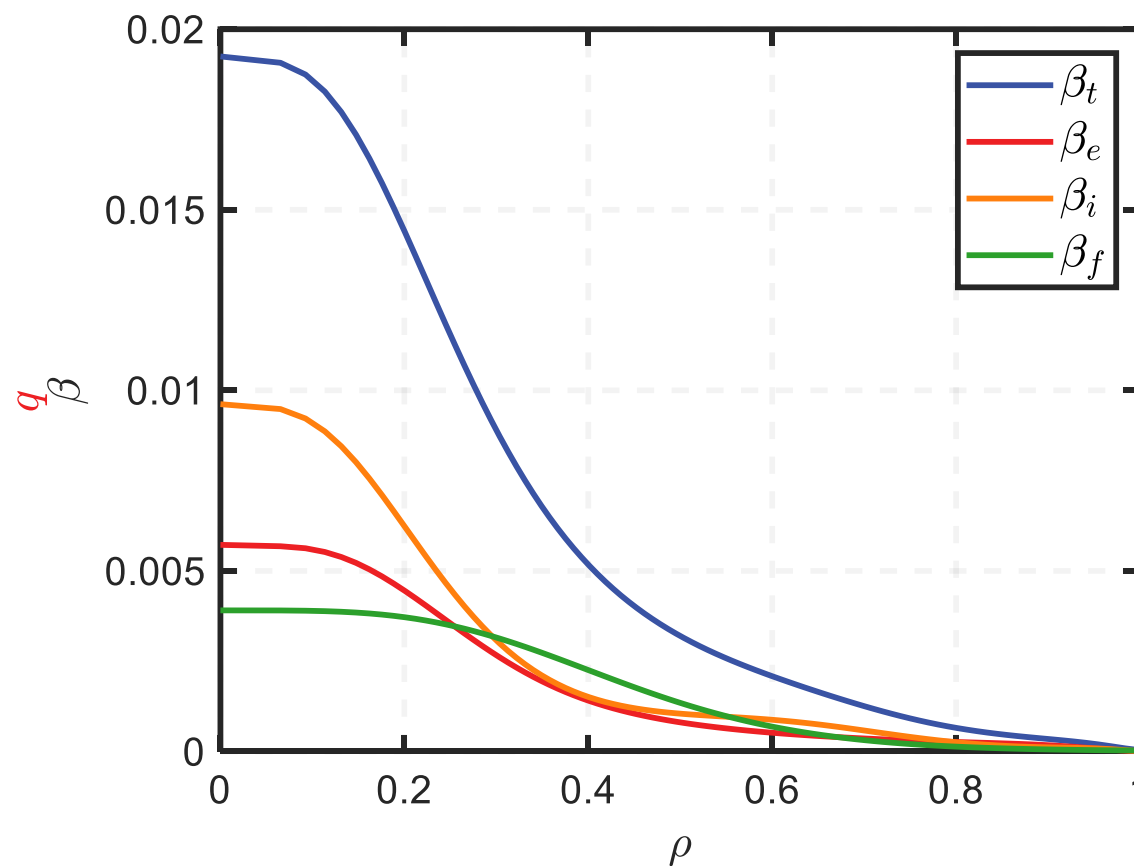
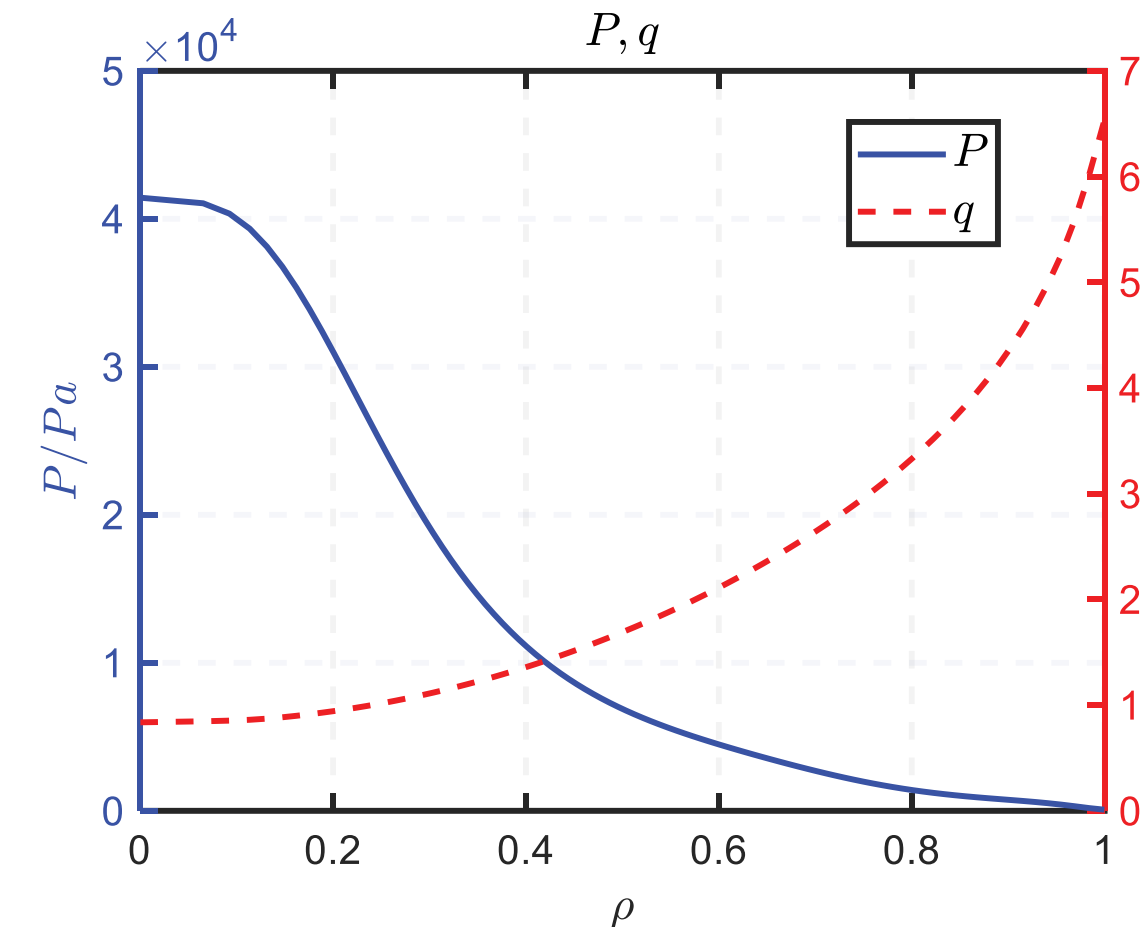


- The left panel shows the ray tracing and the measurement positions of the Doppler reflectometry system.
- The 4-channel provides simultaneous reliable measurements at different radial locations.
- The right panel shows the flow at several times during the fishbone bursts. Reversed flow structure inside the $q = 1$ resonant surface, with a similar amplitude for different bursts.

Outline

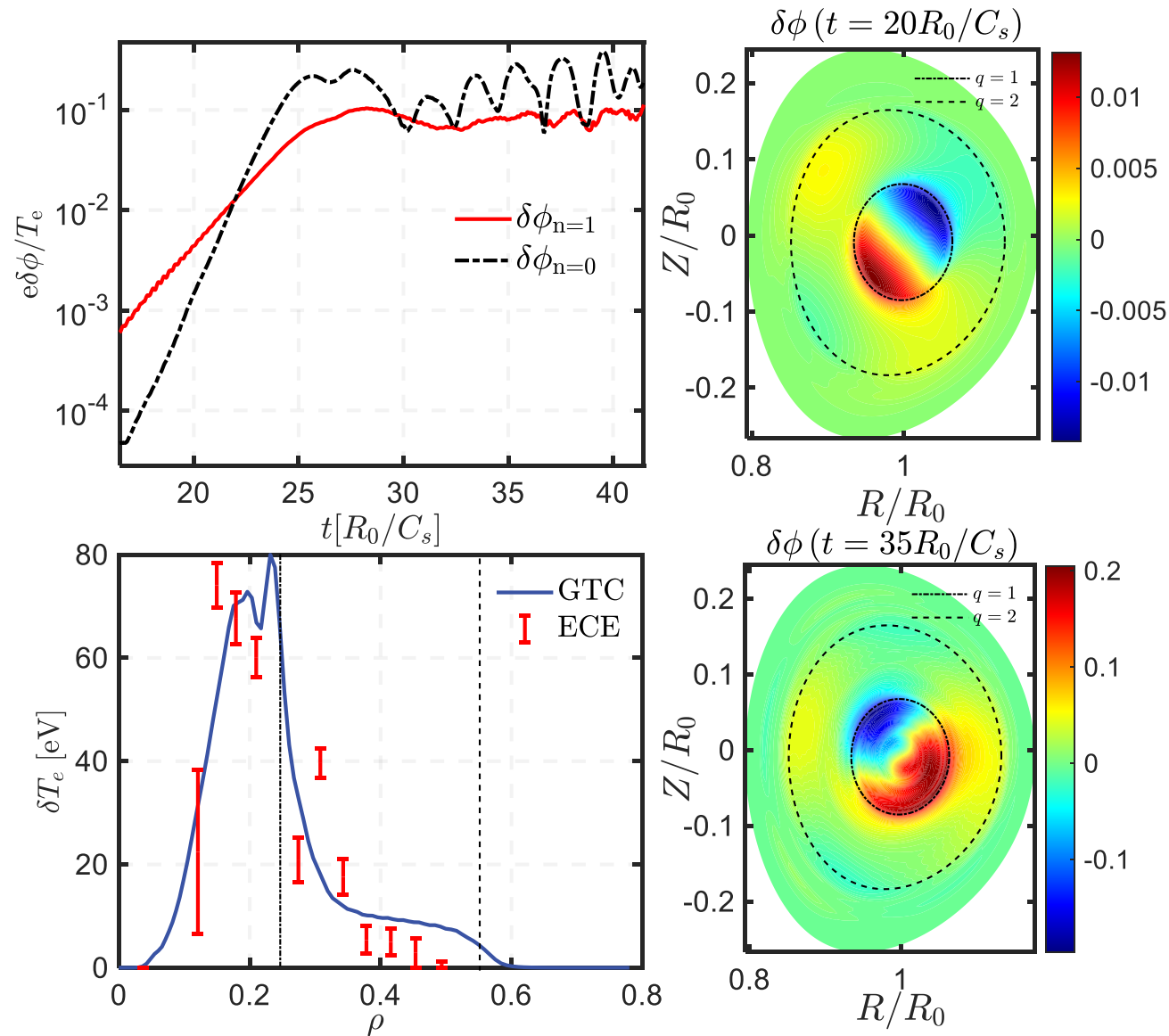
- ◆ Background and Motivation
- ◆ Experimental results
- ◆ **Fishbone simulation results**
- ◆ Conclusions

EAST #133556 equilibrium parameters



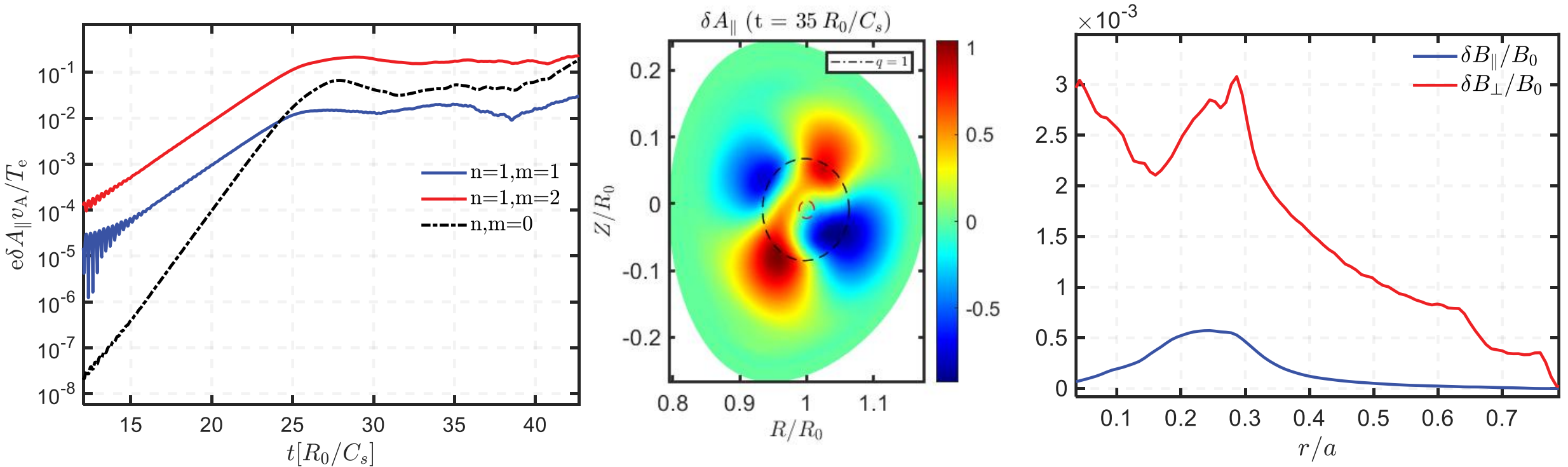
- The equilibrium is reconstructed by kinetic EFIT for EAST discharge #133556 at $t = 3.72$ s.
- Normal magnetic shear q profile, with the $q = 1$ rational surface located at $\rho \approx 0.25$.
- The total plasma beta is $\beta \approx 1.9\%$, while the fast-ion $\beta_f \approx 0.4\%$, small fast ion density $n_f/n_{e0} = 0.13$.

Fishbone nonlinear gyrokinetic simulation using GTC



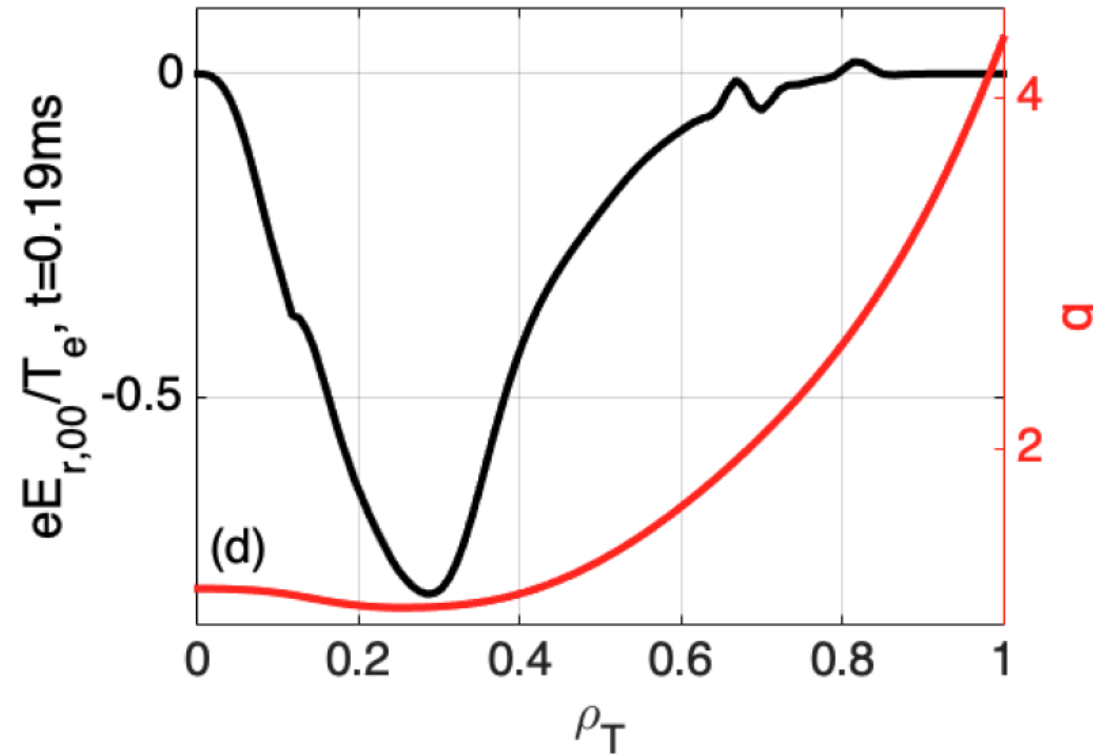
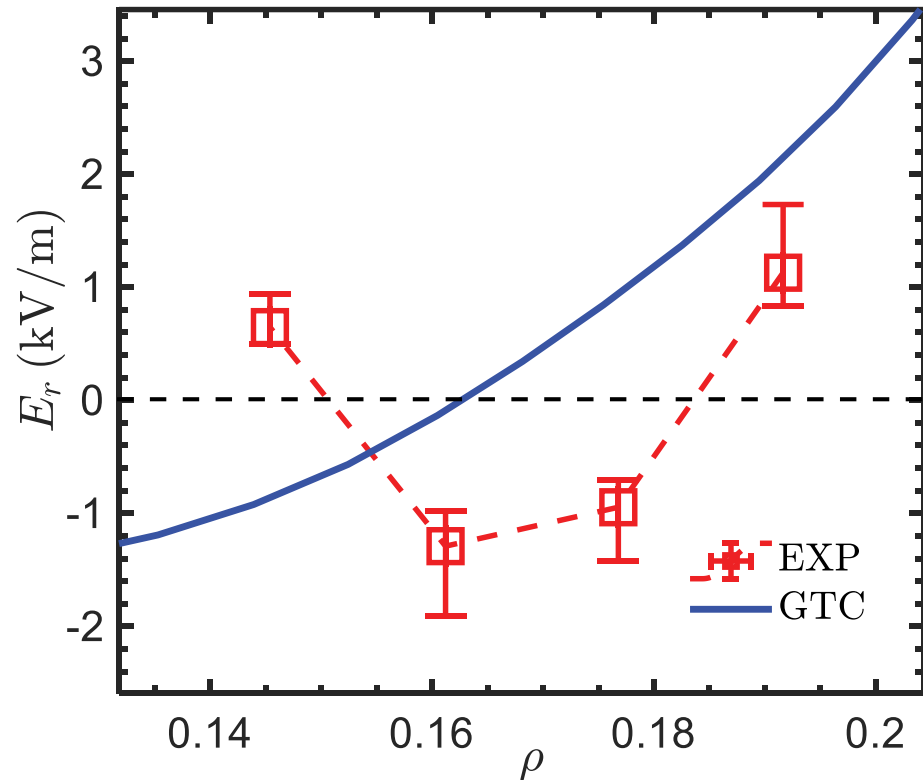
- The GTC simulations retain only the $n = 1$ toroidal mode together with the $n = m = 0$ zonal flows.
- The $n = 1$ fishbone grows with a linear growth rate $\gamma_{n=1} = 9.78 \times 10^4$ rad/s and mode frequency 20.8 kHz.
- $\delta\phi_{00}$ increases exponentially at a rate $\gamma_{n,m=0} \approx 2\gamma_{n=1}$ indicating that the zonal flows are generated by fishbone through the beat-driven process.
- The good agreement in δT_e with the ECE measurements further validates our simulation.

Fishbone gyrokinetic simulation magnetic perturbation



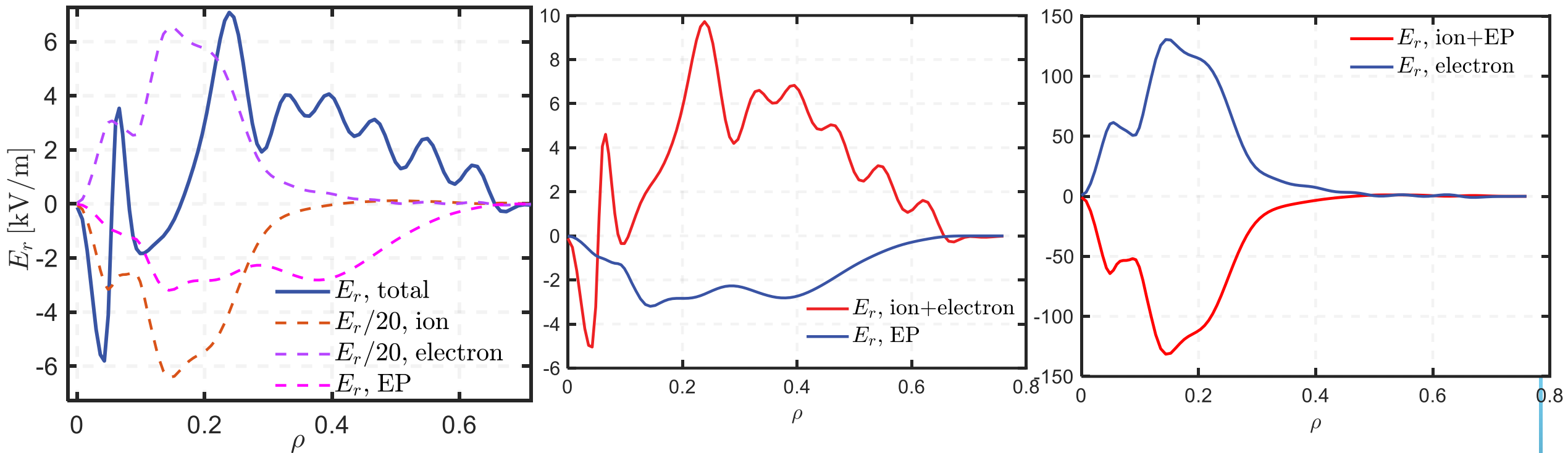
- During the time evolution, the $m = 2$ poloidal sideband of $\delta A_{||}$ has a larger amplitude;
- The zonal component of $\delta A_{||}$ is smaller than the $n = 1$ component;
- The magnetic perturbation reaches saturation at the amplitude of $\delta B_{\perp}/B_0 \sim 3 \times 10^{-3}$.

Fishbone induce the radial electric field



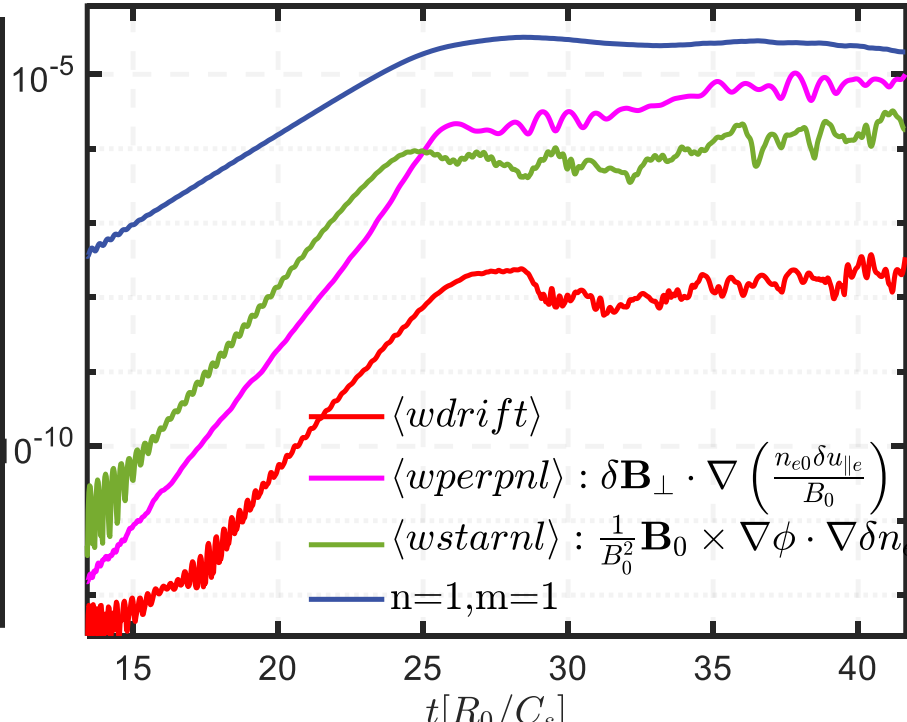
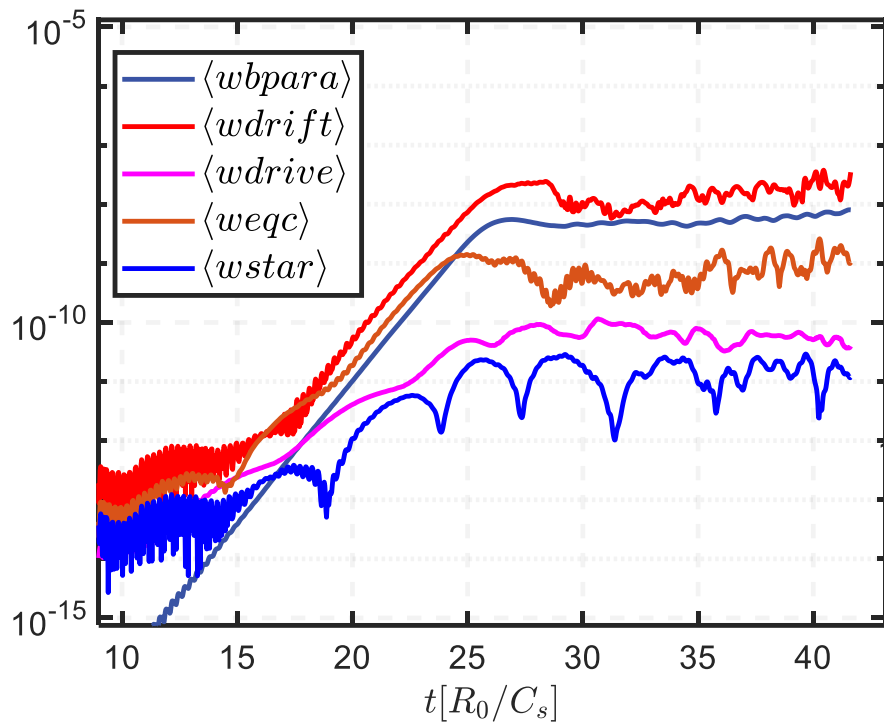
- Reversed radial structure of the zonal radial electric field within $q = 1$ rational surface;
- GTC simulation results agree with DR measurements, with comparable amplitudes of the electric field.
- In contrast to the well-like zonal electric fields obtained in DIII-D simulations. The difference is attributed to the self-consistent inclusion of zonal electron density response in our simulation model.

Contributions to the zonal radial electric field



- The fine radial structure is determined by both the thermal ions and electrons rather than fast ions. Fast ions make a modest contribution, predominantly to the large-scale $k_r \approx 0$ component;
- When only zonal density of ions and EPs are included, also obtained the well-like zonal electric field; Similar to the mean flow E_r and the zonal electric fields in DIII-D simulations;
- The zonal electron density is crucial; counteract the zonal ion density and weakens the field amplitude.

Contributions to the evolution of zonal electron density



- w_{*nl} the nonlinear $E \times B$ convection term of δn_e
- $w_{\perp nl}$ the electromagnetic magnetic flutter coupling between $\delta B_\perp$ and the parallel electron flow.

$$\frac{\partial \delta n_e}{\partial t} + \underbrace{\mathbf{B}_0 \cdot \nabla \left(\frac{n_{0e} \delta u_{||e}}{B_0} \right)}_{w_{||}} + \underbrace{\left(-n_{0e} \mathbf{v}_* \cdot \frac{\nabla B_0}{B_0} \right)}_{w_{drive}} + \underbrace{\left(\delta \mathbf{B}_\perp \cdot \nabla \frac{n_{0e} u_{||0e}}{B_0} + \dots + \frac{\delta n_e}{B_0^2} (\nabla \times \mathbf{B}_0) \cdot \nabla \phi \right)}_{w_{eqc}} +$$

$$\underbrace{\frac{1}{B_0^2} \mathbf{B}_0 \times \nabla \phi \cdot \nabla n_{0e}}_{w_*} + \underbrace{\left(-\frac{2(n_{0e} + \delta n_e)}{B_0^3} \mathbf{B}_0 \times \nabla \phi \cdot \nabla B_0 \right)}_{w_{drift}} + \underbrace{\frac{1}{B_0^2} \mathbf{B}_0 \times \nabla \phi \cdot \nabla \delta n_e}_{w_{*nl}} +$$

$$\underbrace{\delta \mathbf{B}_\perp \cdot \nabla \left(\frac{n_{0e} \delta u_{||e}}{B_0} \right)}_{w_{\perp nl}} + \underbrace{\left[-\frac{\mathbf{b}_0 \times \nabla \delta B_{||}}{e} \cdot \nabla \left(\frac{P_{\perp 0e} + \delta P_{\perp e}}{B_0^2} \right) - \frac{(\nabla \times \mathbf{b}_0) \cdot \nabla \delta B_{||}}{e B_0^2} (P_{\perp 0e} + \delta P_{\perp e}) \right]}_{w_{b||}} = 0$$

- Zonal electron density is generated by the combined nonlinear convection and magnetic flutter transport.

Outline

- ◆ Background and Motivation
- ◆ Experimental results
- ◆ Fishbone simulation results
- ◆ **Conclusions**

Conclusions

- The zonal flow driven by the fishbone instability has been directly measured for the first time in the EAST tokamak.
- Zonal flow exhibits faster rise rates than fishbones in early stage, the fine and reversed structure within the $q = 1$ surface, more like beat-driven zonal flows.
- This flow originates from the zonal radial electric field generated by the fishbone instability. GTC simulation results show agreement with Doppler Reflectometry.
- The zonal electron density is crucial; it can counteract the ion zonal density. This cancellation weakens the zonal electric field.



中国科学技术大学

University of Science and Technology of China

Thank you for listening !