27th IAEA Fusion Energy Conference, 22-27 October 2018, Gandhinagar, India **TH/1-1**

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Simulations of energetic particle driven instabilities and fast particle redistribution in EAST tokamak

Wei Shen[1], Youbin Pei[1,2], Yingfeng Xu[1], G. Y. Fu[3,4], Feng Wang[5], Nong Xiang[1], Youjun Hu[1], Y. Todo[6], Wenfeng Guo[1], Lei Ye[1], Xiaotao Xiao[1], Shaojie Wang[2], Deng Zhou[1], Liqing Xu[1], Guoqiang Li[1], Juan Huang[1], Chengyue Liu[1], Siqiang Zhu[2]

[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

[4]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, United States of America

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

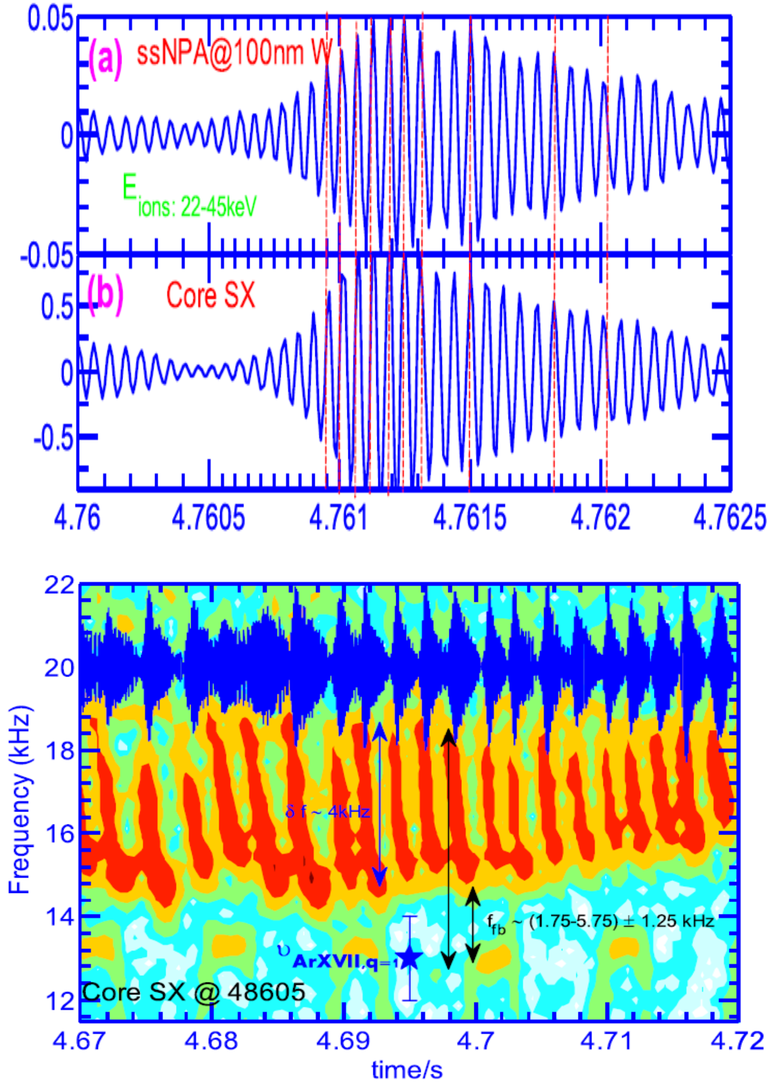
[6]National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

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

Outline

- Introduction
- Simulation of fishbone instability
- Simulation of toroidal Alfvén eigenmodes
- Simulation of RMPs induced fast particle transport
- Summary

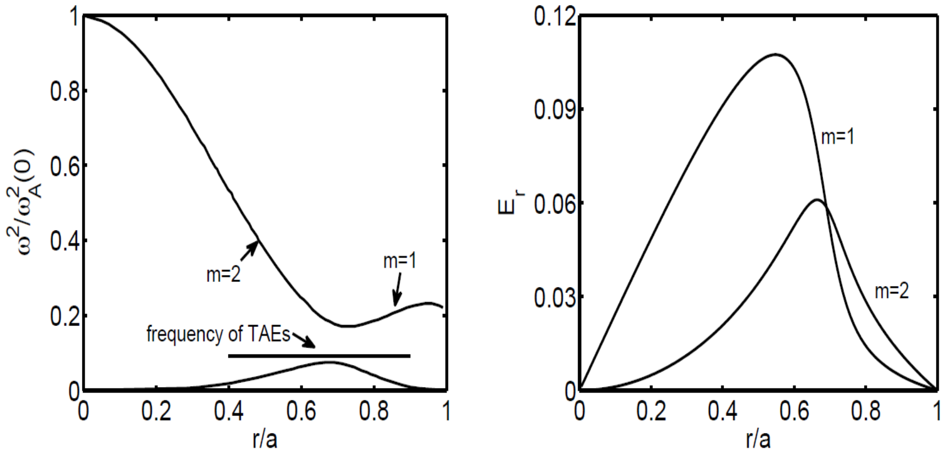
Introduction I



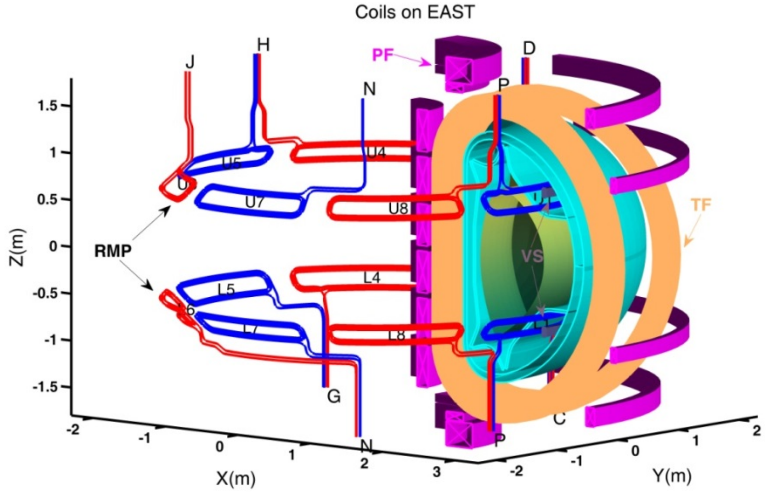
L. Q. Xu et al. POP 2015

- **Energetic particle physics is a crucial issue in magnetic fusion reactor such as ITER.**
- **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]. The fishbone instability was observed in EAST experiment with NBI heating for the first time in 2014[L. Q. Xu et al. POP 2015].**

Introduction II



L. M. Yu PhD thesis 2009



From Y. W. Sun's presentation

- Toroidal Alfvén eigenmodes (TAEs) are discrete shear Alfvén eigenmodes which can exist inside the toroidicity-induced continuum gaps[C. Z. Cheng et al. Ann. Phys. 1984].
- The resonant magnetic perturbations (RMPs) induced by external coils can lead to redistribution and even significant loss of energetic particles.
- Instabilities driven by energetic particles including fishbones and TAEs, together with fast particle loss and heat load due to RMPs, are investigated numerically with codes M3D-K, MEGA, and GYCAVA in EAST tokamak.

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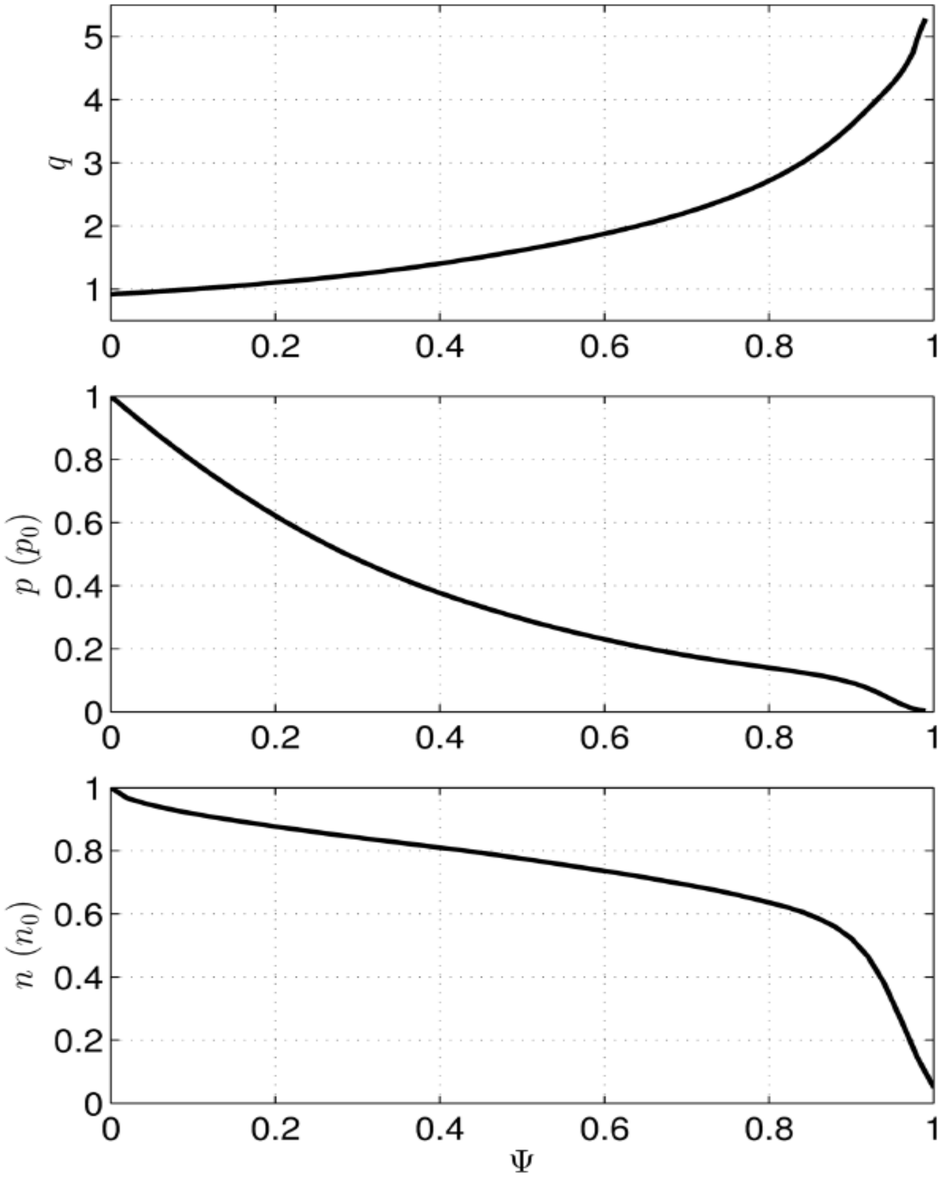
Basic parameters and initial profiles

Main parameters in EAST Shot #48605:

- **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: $\beta_{total,0}$=3.45%**
- **central beam ion beta: $\beta_{hot,0}$=0.86%**



Beam ion distribution function:

$$f = c\left(\sum_{i=1}^{3} c_i \frac{H(v_0/\sqrt{i}-v)}{v^3+v_c^3}\right) exp(-(\Lambda-\Lambda_0)^2/\Delta\Lambda^2) exp(-\langle\Psi\rangle/\Delta\Psi),$$

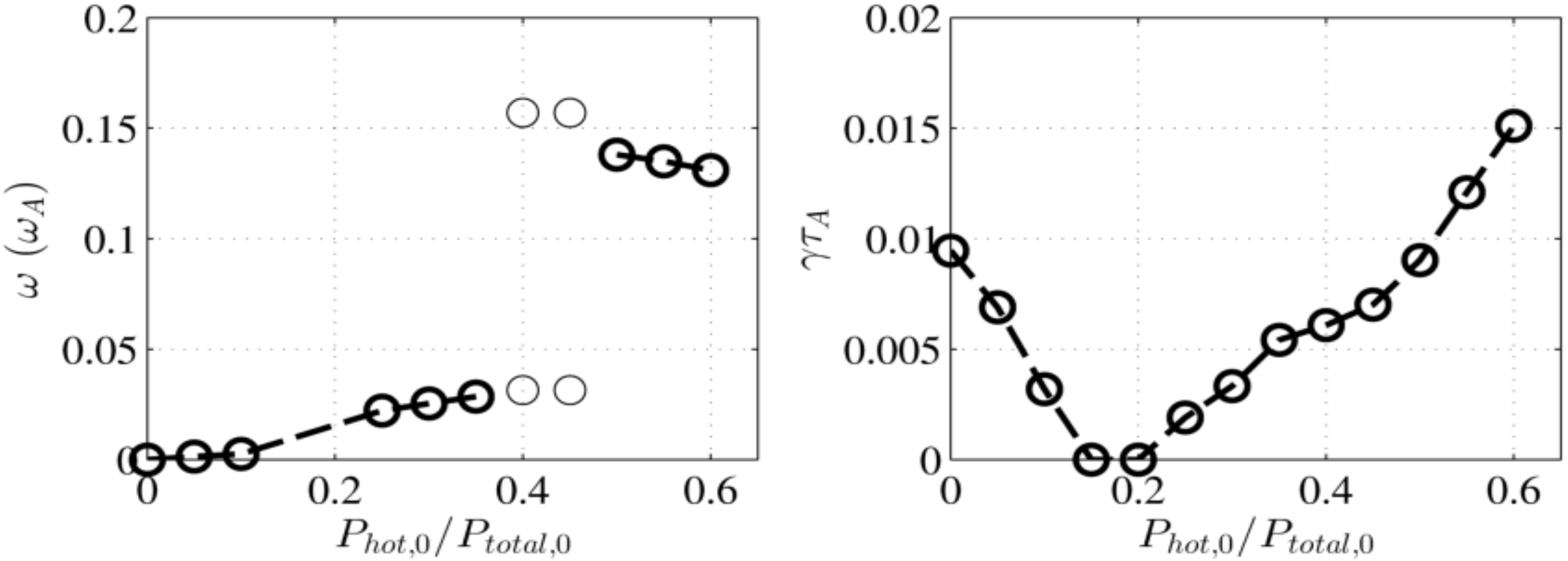
$$\Lambda \equiv \mu B_0/E \qquad \Lambda_0 = 0.8,\ \Delta\Lambda = 0.5,\ \Delta\Psi = 0.3,$$

The injection energy of NBI is E_0 = 60 keV.

Also NBI of E_0/2 and E_0/3 are included.

Fishbone transits to BAE when beam pressure increases

- $P_{hot,0}/P_{total,0}$ increases, the mode is firstly stabilized and then destabilized.
- $P_{hot,0}/P_{total,0}$ is larger than 0.2, the fishbone instability is excited.
- $P_{hot,0}/P_{total,0}$ increases further, fishbone transits to BAE.
- $P_{hot,0}/P_{total,0}$=0.4 and 0.45: two different linear mode frequencies.



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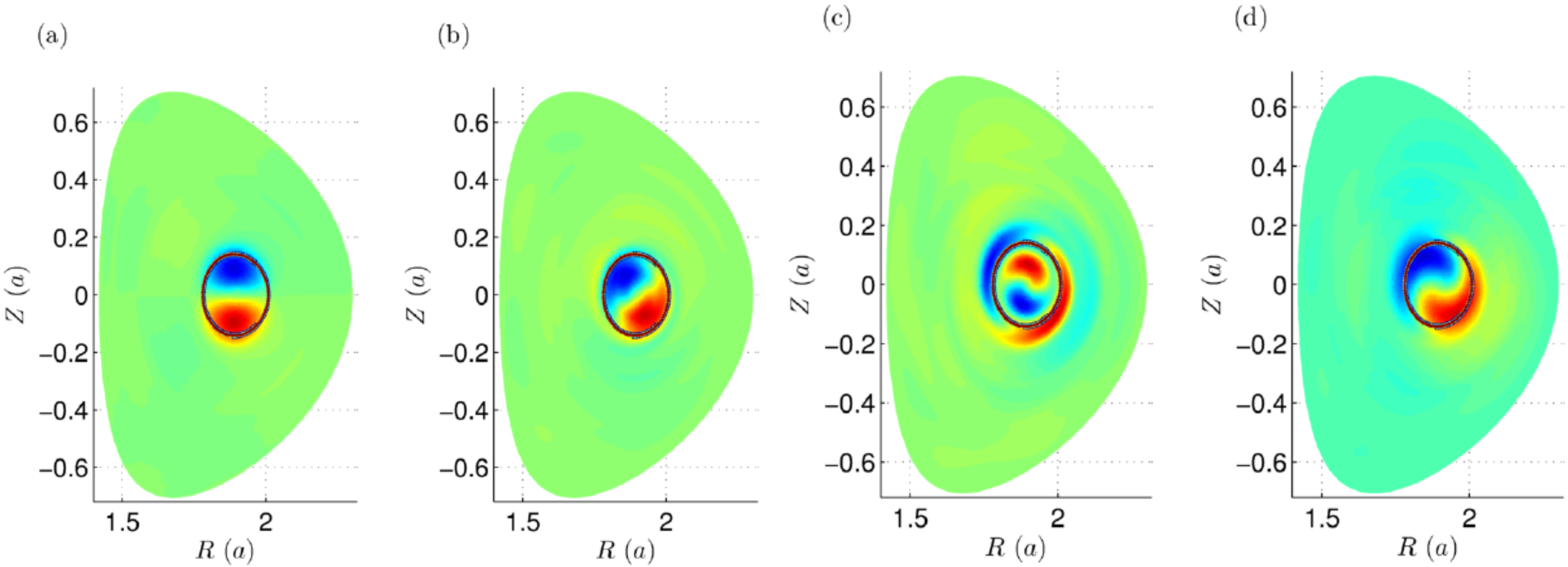
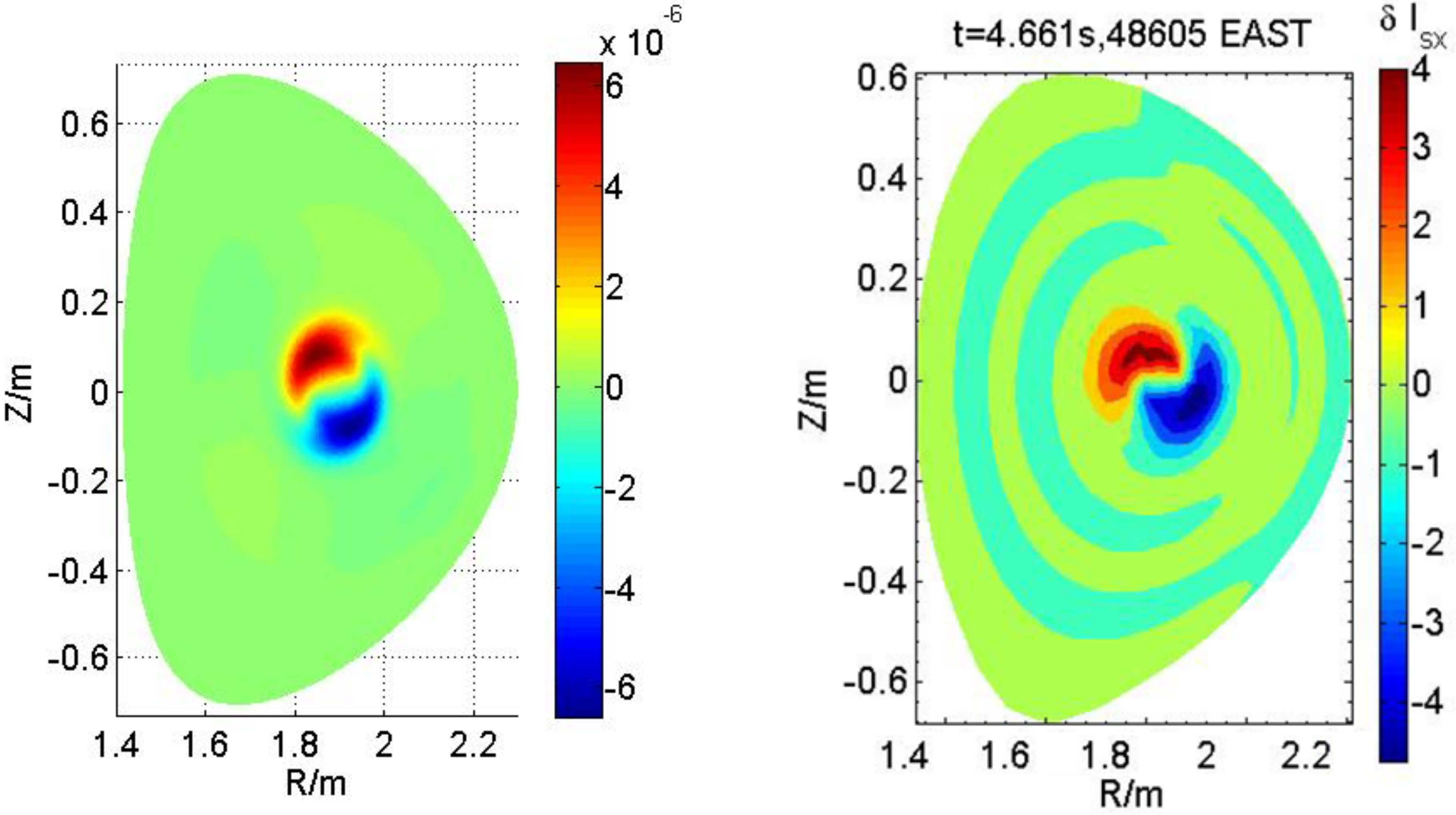
Mode structure changes when beam pressure increases

- $P_{hot,0}/P_{total,0}$=0: up-down symmetric (Fig. (a)).
- $P_{hot,0}/P_{total,0}$=0.25: fishbone structure twisted (Fig. (b)).
- $P_{hot,0}/P_{total,0}$=0.4: double m/n = 1/1 mode structures coexist (Fig. (c)).
- $P_{hot,0}/P_{total,0}$=0.5: BAE mode peaked around q=1 surface(Fig. (d)).



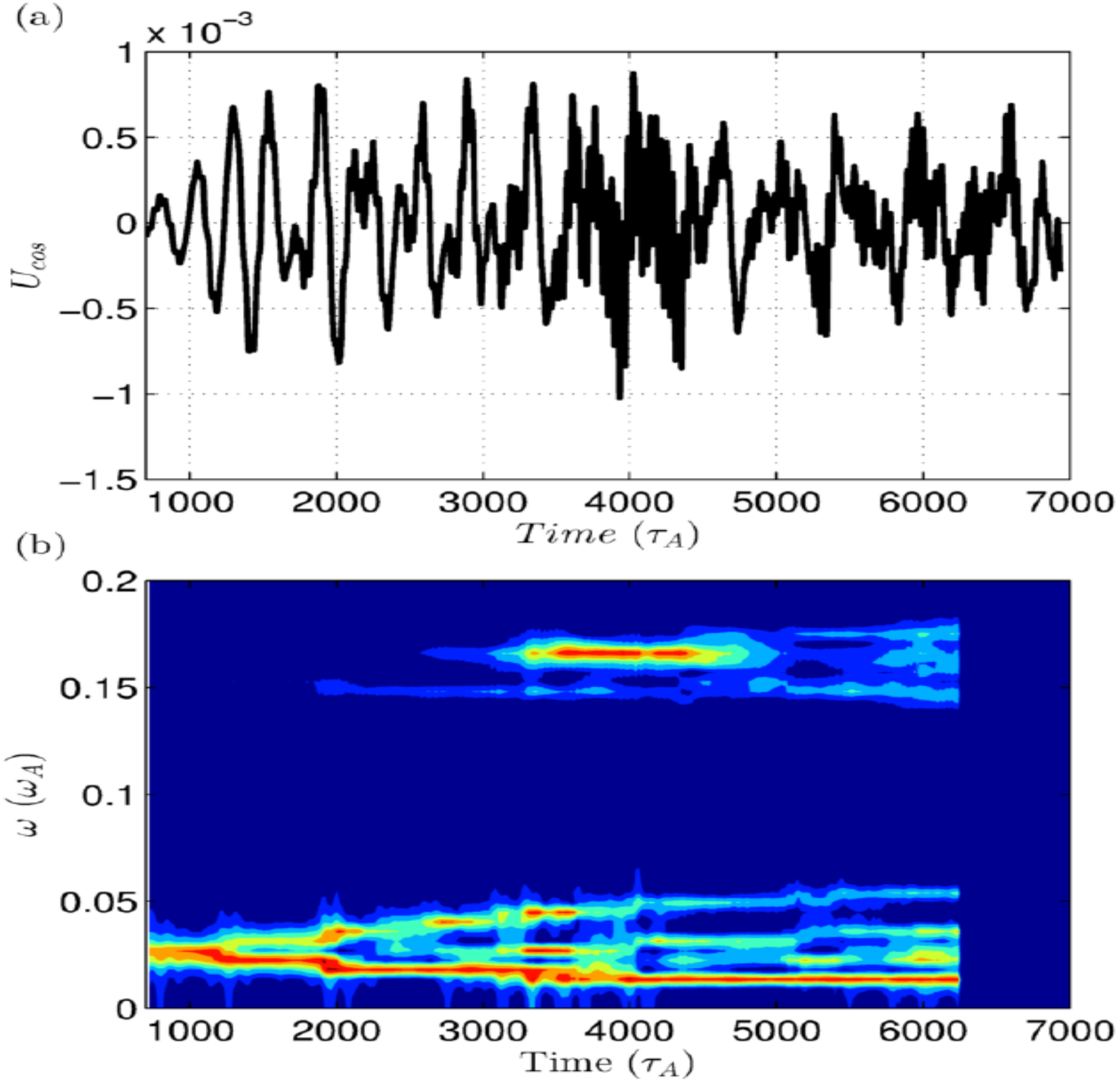
Simulation result agrees well with EAST experiment

- $f_{sim} = (0.022\ \omega_A)/(2\pi) = 6.99$ kHz, consistent with $f_{exp} = 5\sim7$ kHz



Fishbone chirps strongly down with BAE emergence during nonlinear phase

- The mode frequency chirps weakly up and strongly down.
- BAE ($\omega \simeq 0.166\ \omega_A$) emerges during nonlinear phase.
- BAE was not observed in EAST, as $\omega_{exp,max} \simeq 0.117\ \omega_A$



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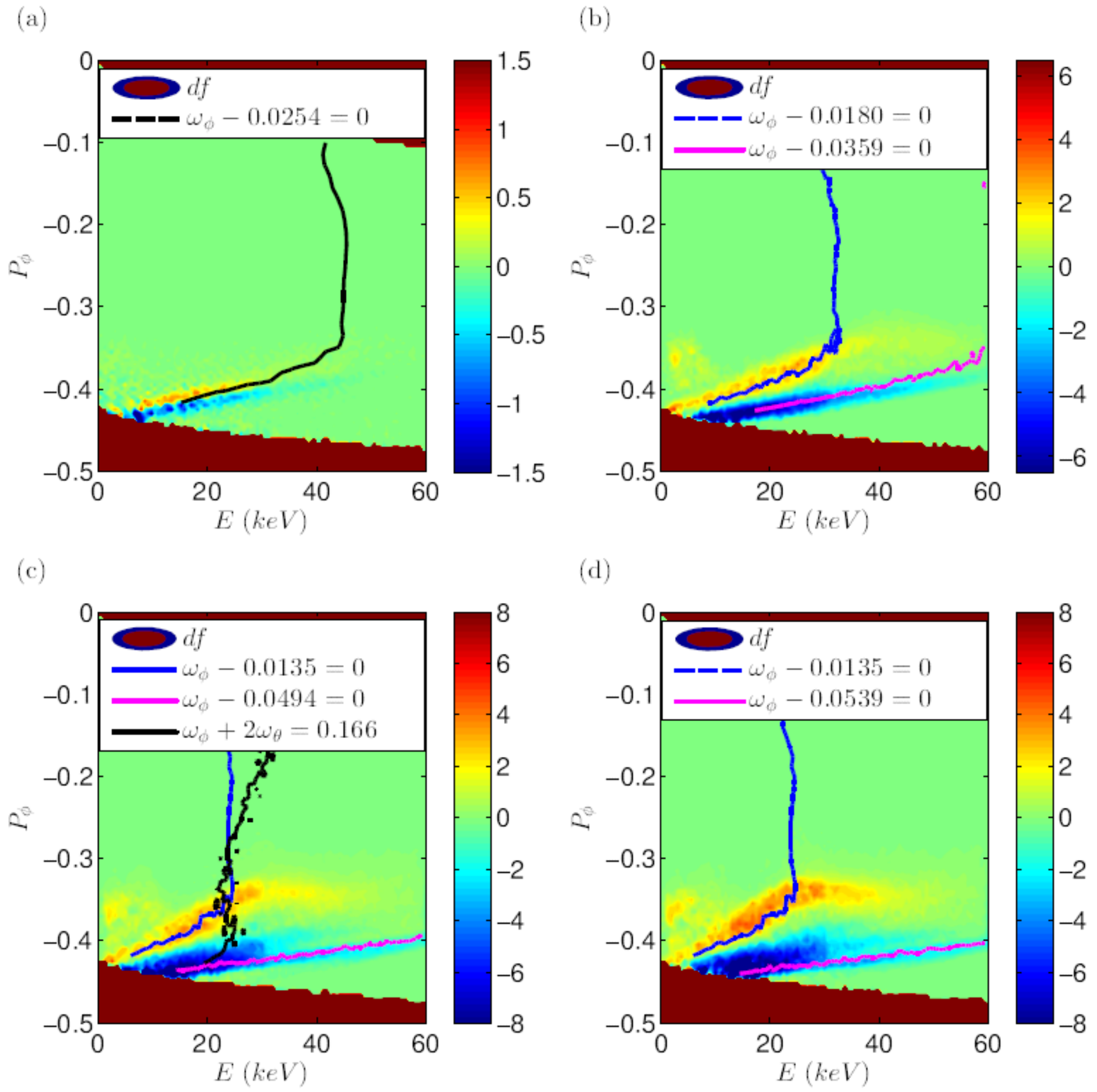
Hole and clump structures emerge during nonlinear phase

- **(a) Linear phase(t = 1000 τ_A): linear resonant condition.**
- **(b) Early nonlinear phase(t = 2500 τ_A): hole and clump structures emerge.**
- **(c) Later nonlinear phase(t = 4500 τ_A): one more resonant condition**
- **(d) t = 6000 τ_A: the flattening region expands outward and inward in P_ϕ direction.**



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Basic parameters and initial profiles

Main parameters based on EAST Shot #38300:

major radius: R_0=1.88 m

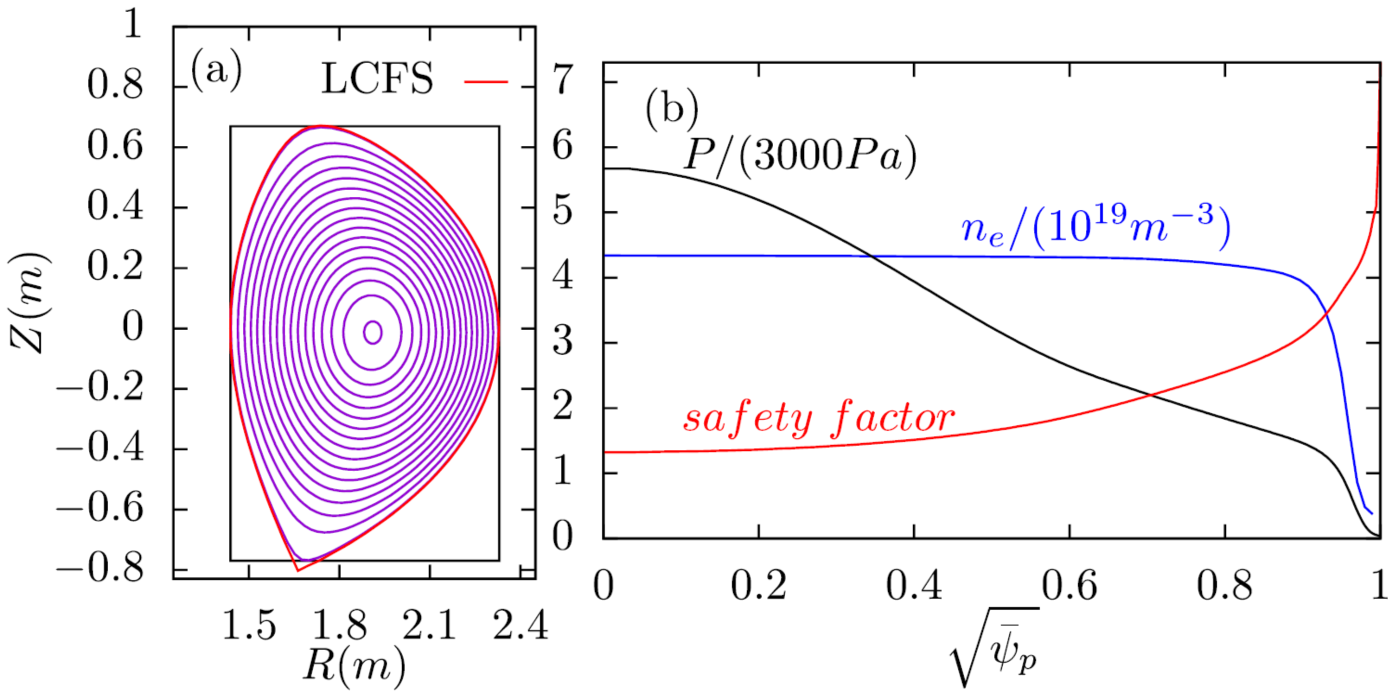
minor radius: a=0.44 m

toroidal magnetic field: B_0=1.64 T

central density: $n_0=4.20\times10^{19}\ m^{-3}$

central total plasma beta: $\beta_{total,0}$=1.88%

central beam ion beta: $\beta_{hot,0}$=0.5%



Beam ion distribution function

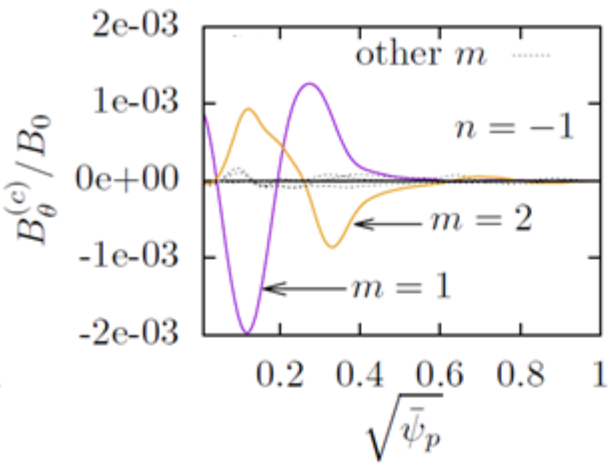
for co-current injection of NBI:

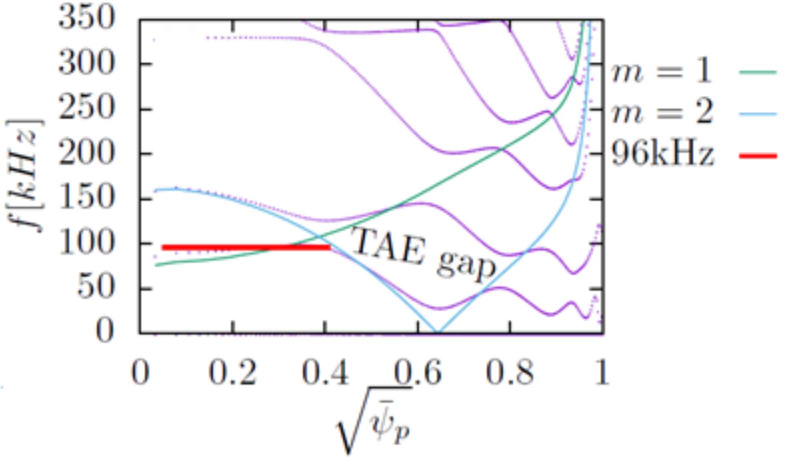
$$f(\bar{\psi}_p, v, \Lambda, \sigma) = Cexp\left(-\frac{\bar{\psi}_p}{\psi_{scale}}\right)\frac{1}{v^3+v_{crit}^3}erfc\left(\frac{v-v_b}{\Delta v}\right)\exp\left(-\frac{(\Lambda-\Lambda_0)^2}{\Delta\Lambda^2}\right)H(-\sigma)$$

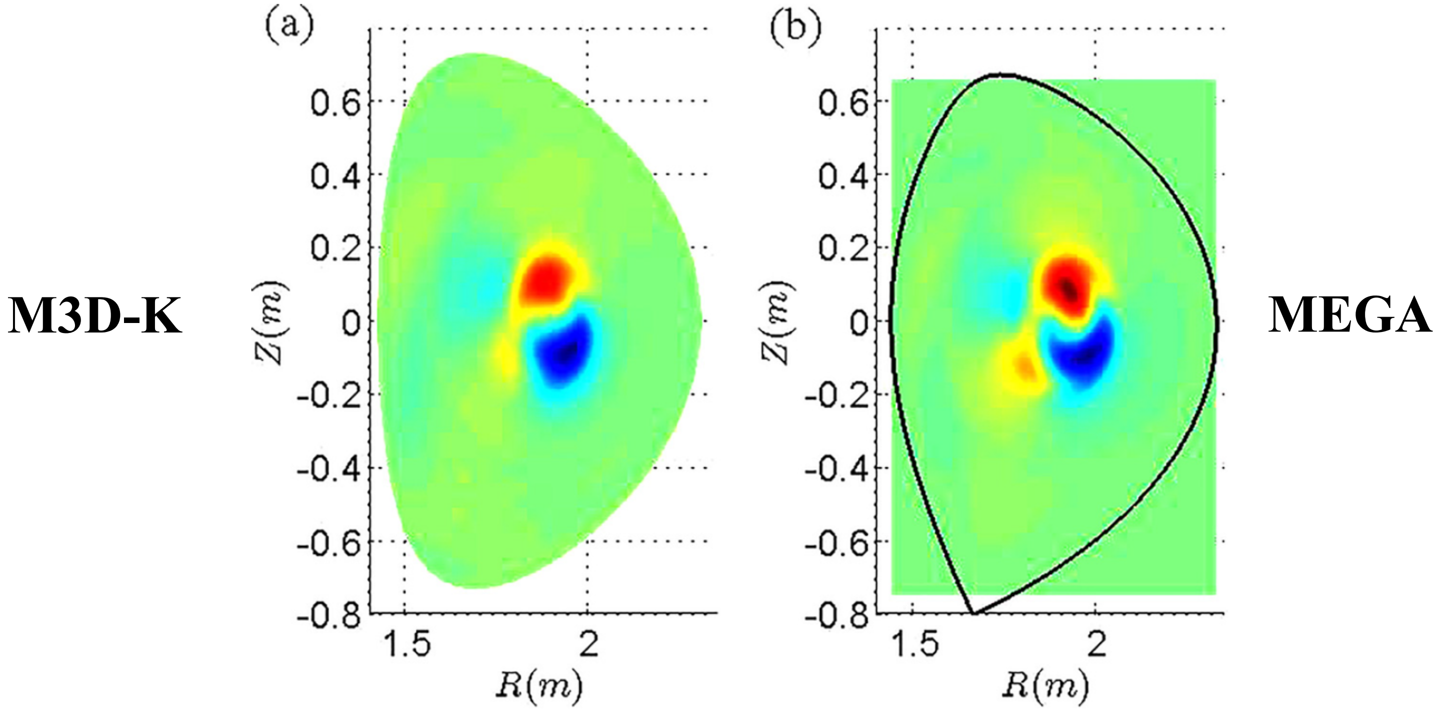
$$\sigma = \mathrm{sgn}(v_{\parallel}),\ \Lambda = \frac{\mu B_0}{E},\ \psi_{\mathrm{scale}} = 0.3,\ v_{crit} = 0.62V_{A0},\ v_b = 0.72V_{A0},\ \Lambda_0 = 0.68$$

TAE structures simulated by M3D-K and MEGA agree with each other

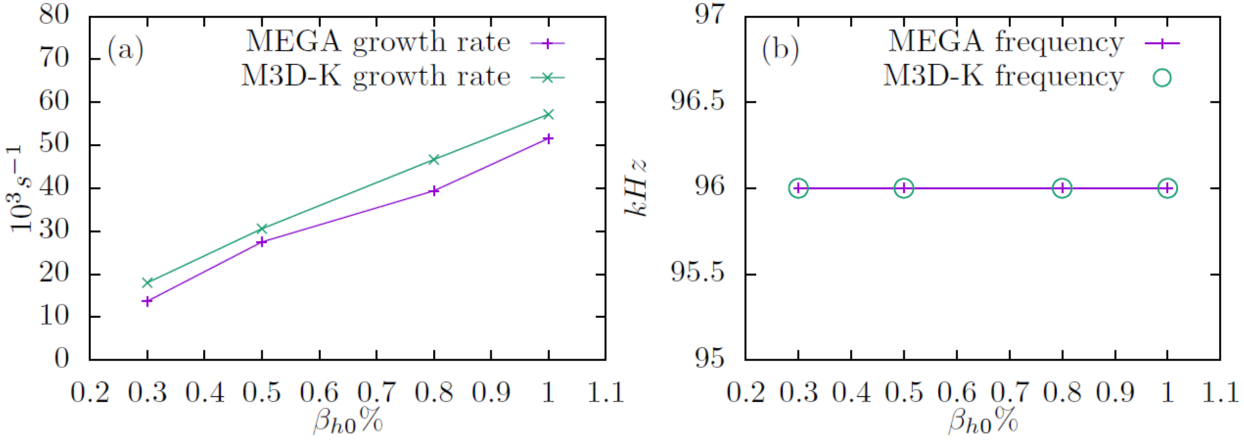
- **The mode is identified as a TAE with n=-1 and dominant m=1, 2 harmonics**
- **The mode structures simulated by M3D-K and MEGA agree with each other.**

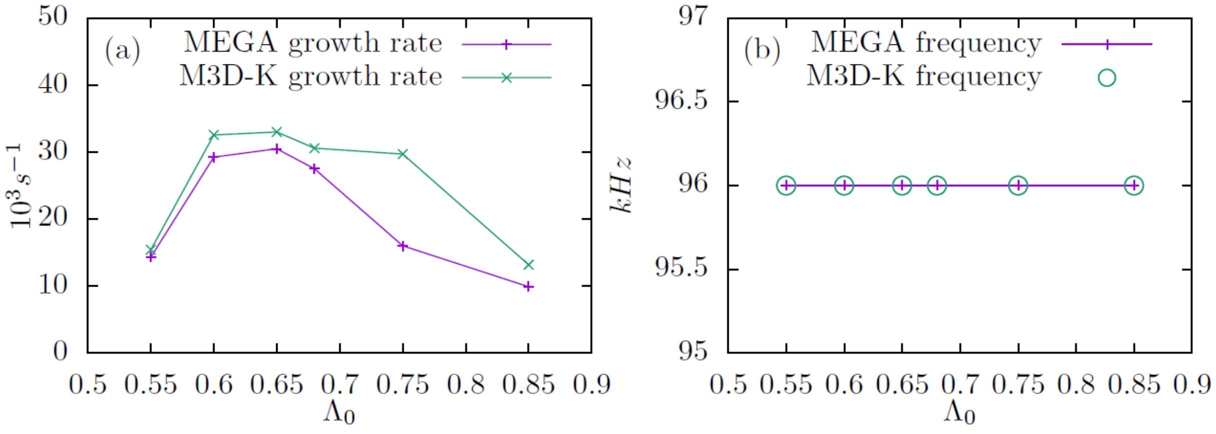


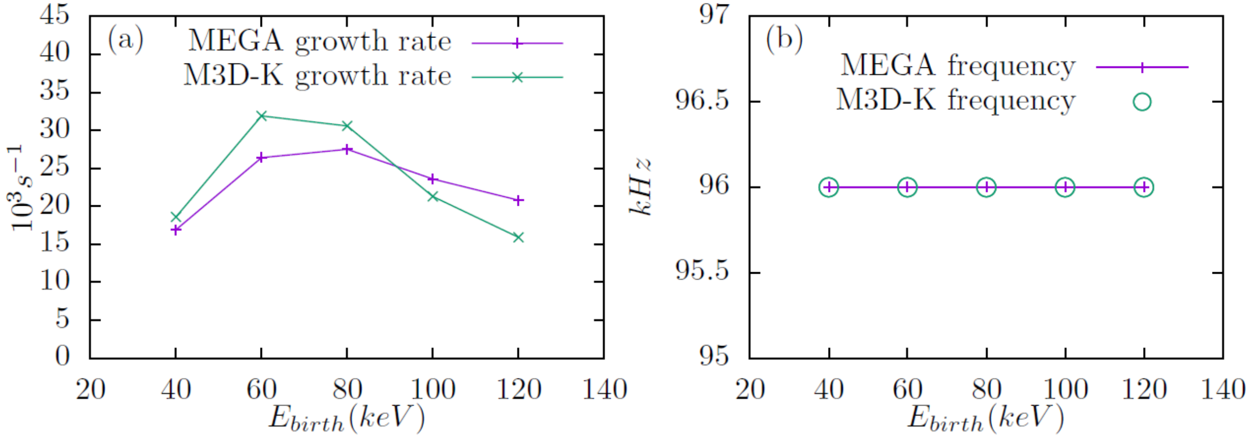




The benchmark between M3D-K and MEGA shows good agreement



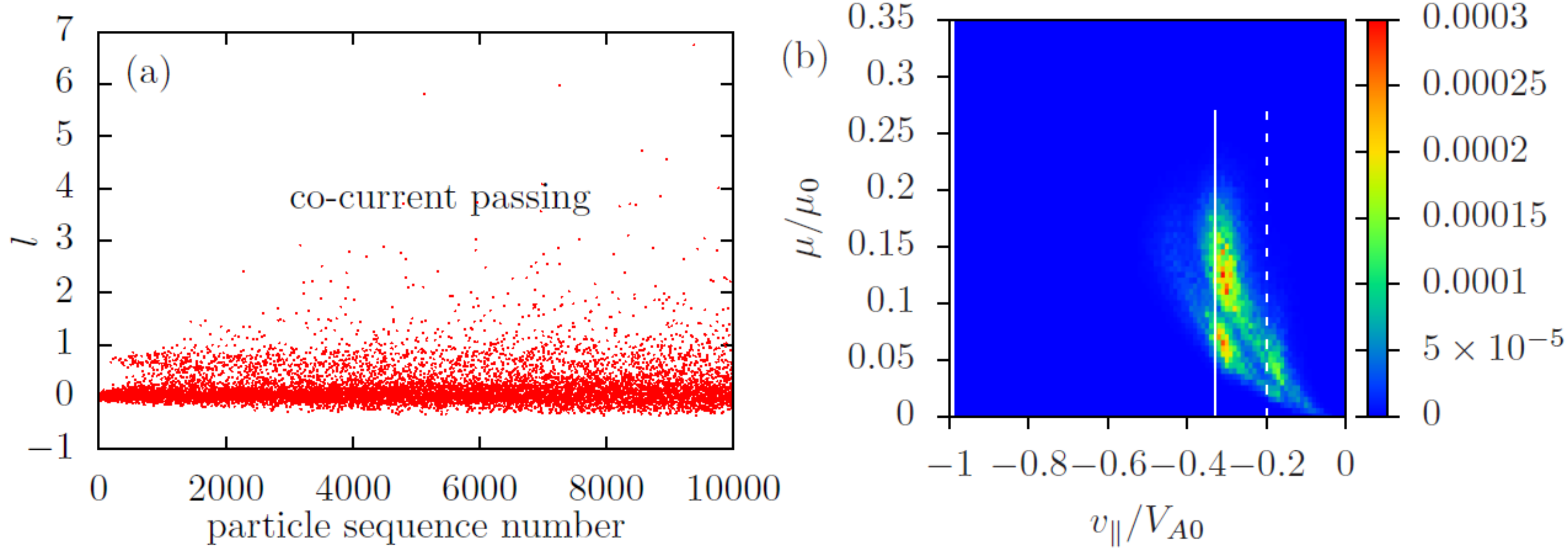




- **Parameter scans show that the frequency and the growth rate of the TAE given by M3D-K and MEGA codes agree with each other.**

The resonant interaction between TAE and co-current passing fast ions is analyzed

- **Resonant condition:** $l = \dfrac{\omega - n\omega_\phi}{\omega_\theta}$



- **For co-current passing fast ions with *l*=0 and *m*=1, 2:** $\omega_\theta = v_\parallel/(qR), \quad \omega_\phi = v_\parallel/R$

$$\boxed{v_\parallel = \frac{V_{A0}}{2l-2m-1} = -\frac{V_{A0}}{3} \text{ or } -\frac{V_{A0}}{5}} \Longleftarrow \omega = V_{A0}/(2qR), \qquad q = |(2m+1)/(2n)|$$

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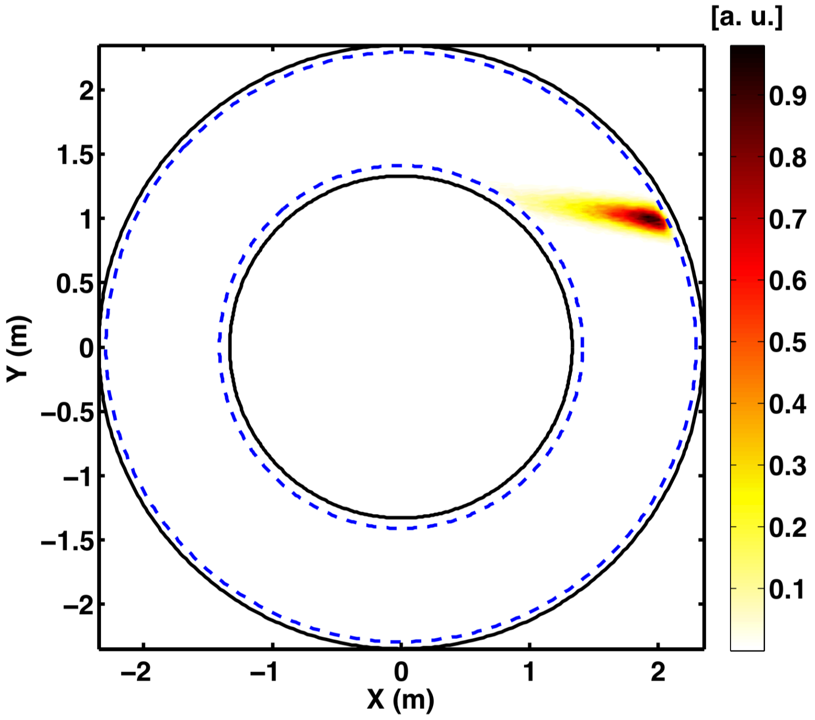
NBI deposition and RMPs on EAST

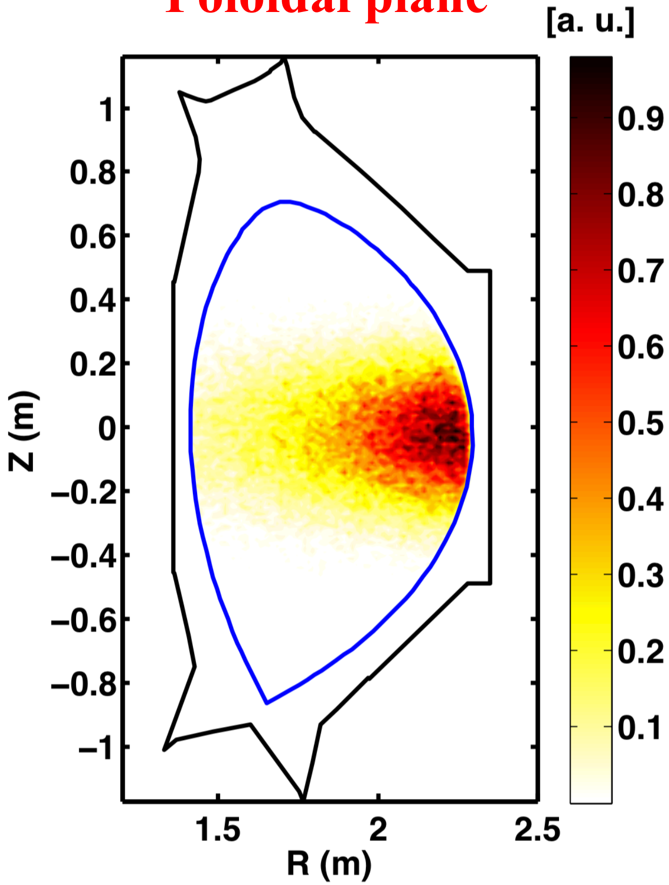
- **birth distribution of NBI on the EAST discharge #55272**

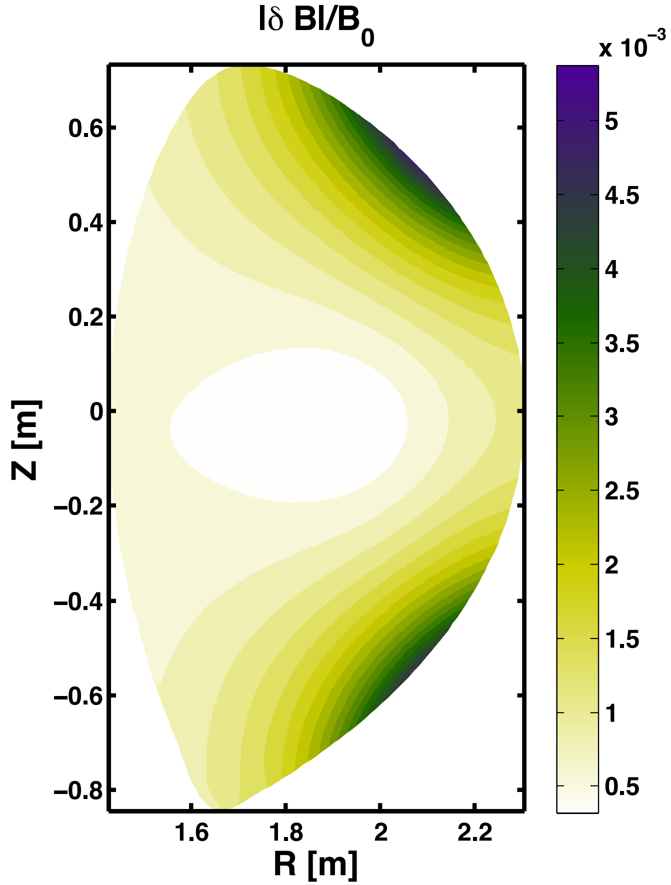
- **RMPs with toroidal mode number n=1 are given by MARS-F without plasma response**

Top view



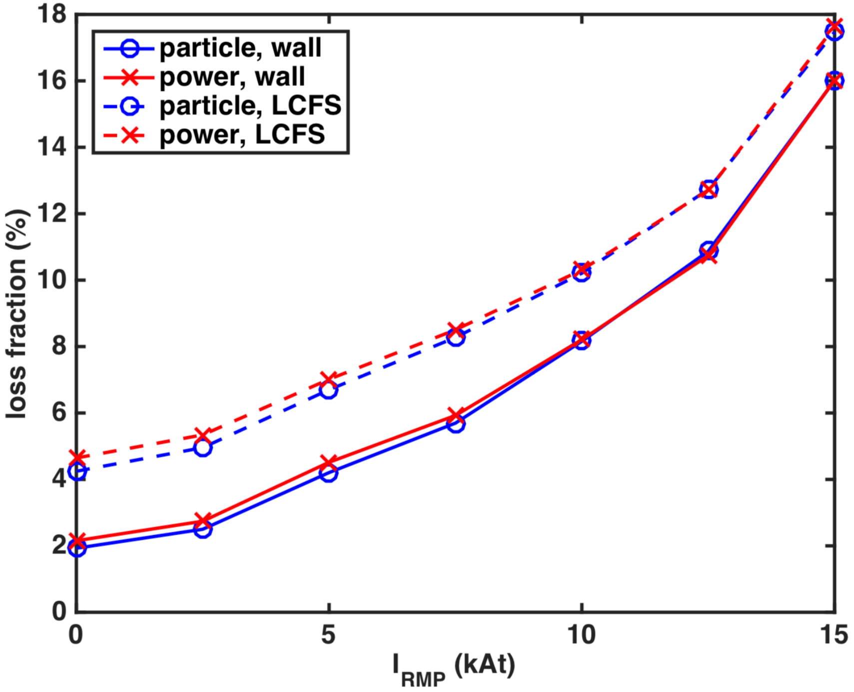
Poloidal plane





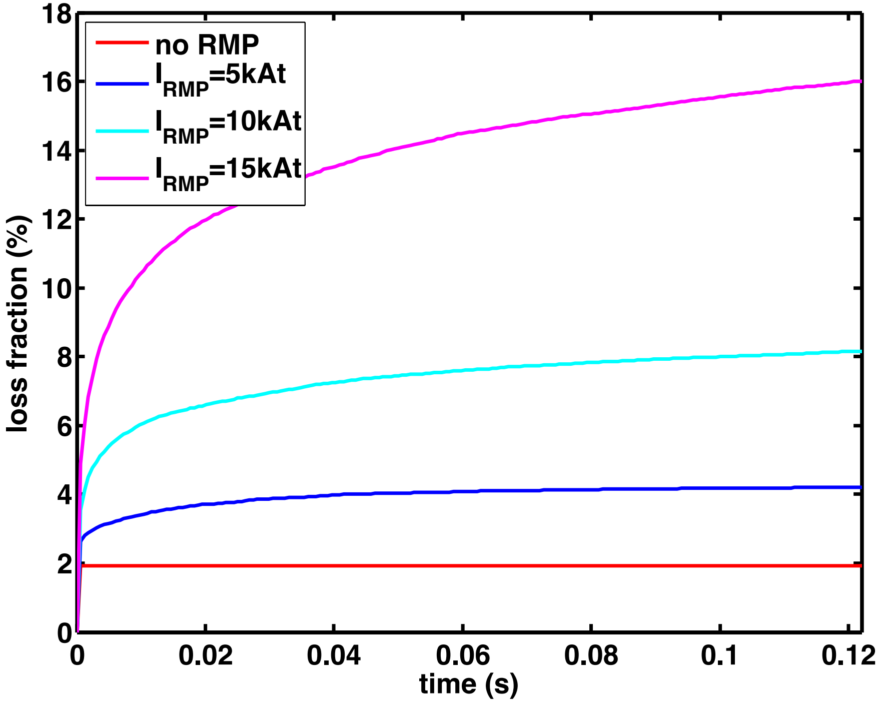
The loss of fast ions increases when the RMP coil current increases

- ➢ **Loss fraction of NBI ions increases with I_{RMP}.**
  - ✓ **I_{RMP}=10 kAt, loss ~ 8% >> loss without RMP (2%).**
  - ✓ **I_{RMP}=15 kAt, loss ~ 16%.**
- ➢ **Loss fraction of particle is similar to that of power.**
- ➢ **Loss with wall boundary < Loss with LCFS boundary; Their difference decreases with I_{RMP}.**



n=1 RMP

E_b=50keV



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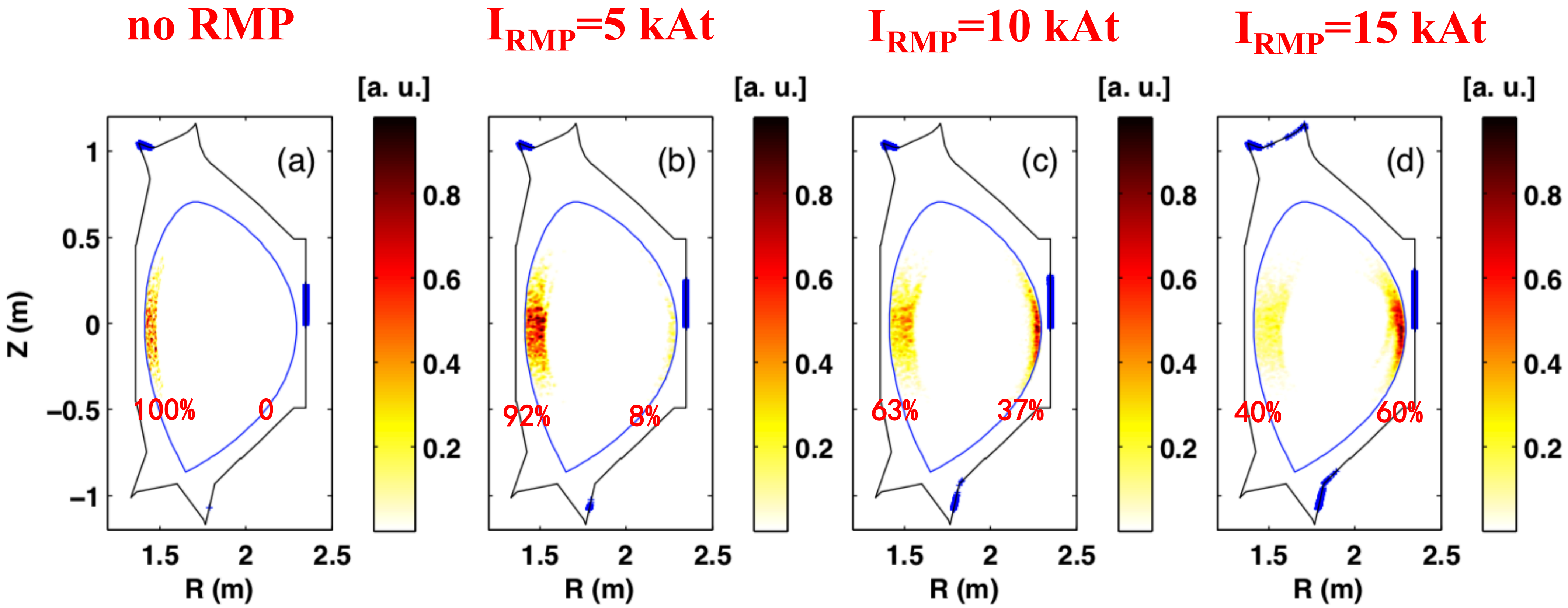
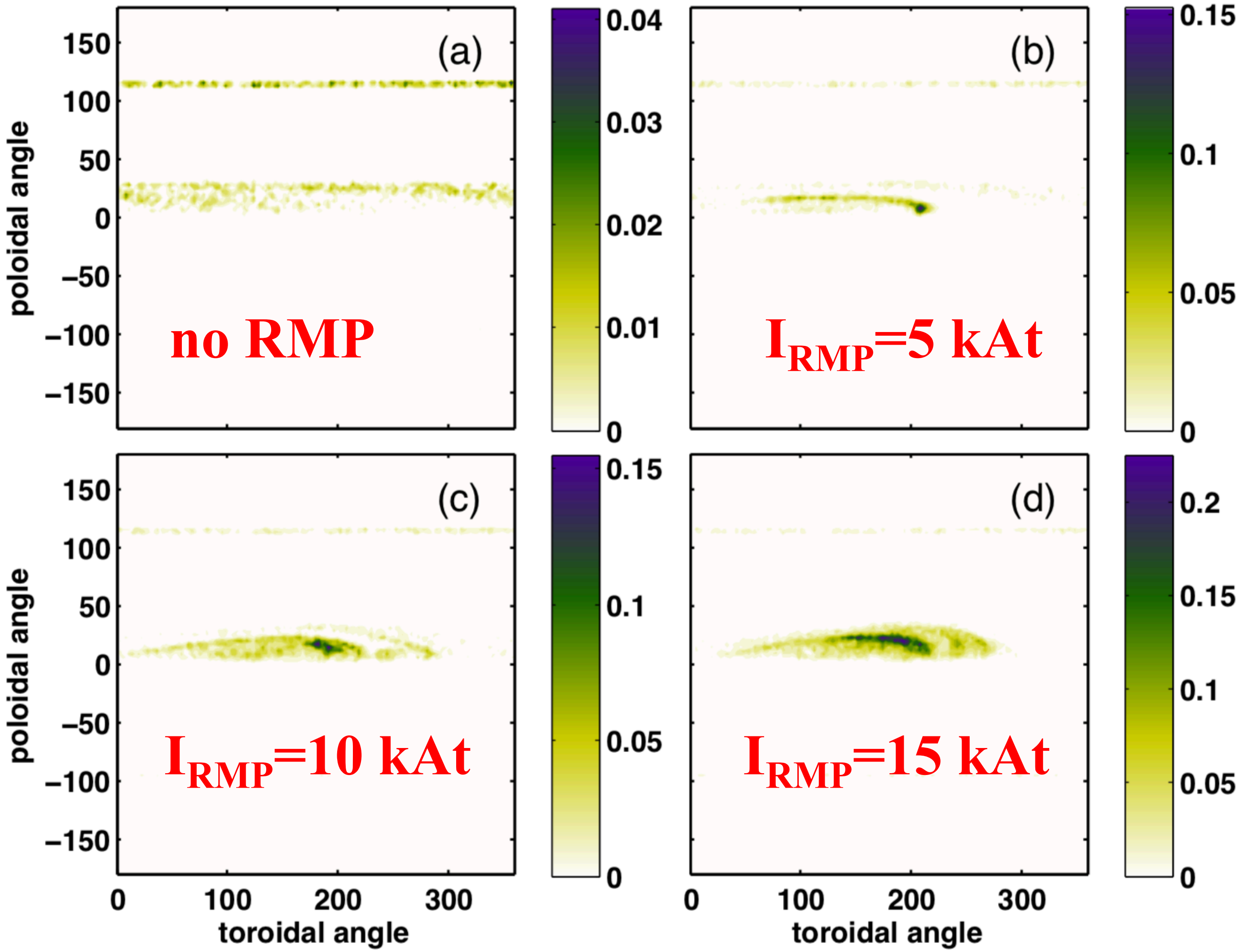
The initial positions of lost fast ions changes with different RMP coil currents



- ➢ **Initial positions of lost fast ions**
  - ✓ **no RMP case: near plasma edge on the high field side.**
  - ✓ **RMP cases: near plasma edge on the low and high field sides.**
- ➢ **Final positions: at outer wall above the mid-plane, near divertors.**

The poloidal distributions of the heat loads are very local



- ➢ The poloidal distributions of heat loads are all very local.
  - ✓ near the upper divertor
  - ✓ on the outer wall above the mid-plane
- ➢ Without RMPs: toroidal distribution is relatively uniform.
- ➢ With RMPs:
  - The heat load is mainly on the outer wall above the mid-plane.
  - The heat load is largest near phi=200°

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Summary and conclusions

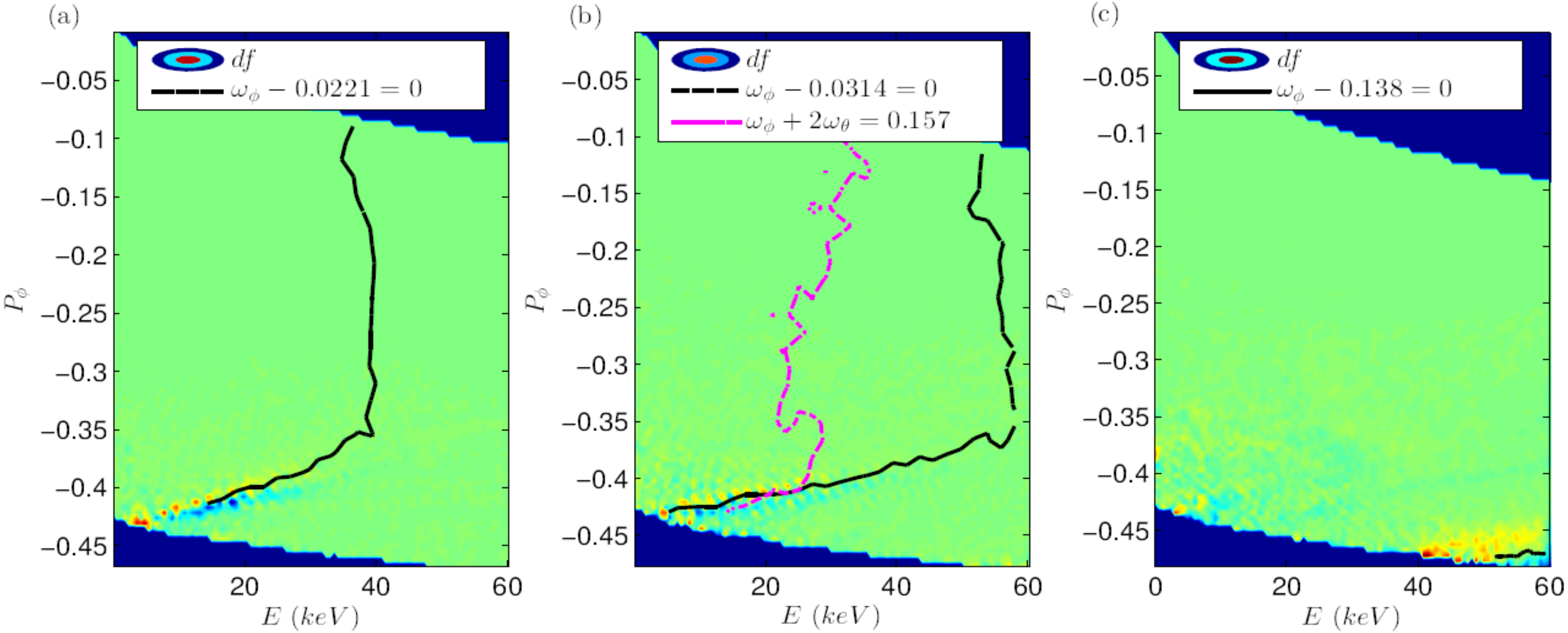
Instabilities driven by energetic particles including fishbones and Alfvén eigenmodes, together with fast particle loss due to RMPs, have been investigated numerically in EAST tokamak.

- **Simulation of fishbone instability:**
  - **The simulated fishbone frequency and mode structure agree well with experimental measurements.**
  - **The frequency chirps up and down with corresponding hole-clump structure formation and movement in the phase space, which agrees with Berk-Breizman hole-clump theory.**
- **Simulation of TAEs:**
  - **The frequency and growth rate of TAEs simulated by MEGA and M3D-K agree with each other.**
  - **The analysis of the resonant interaction shows that the TAE exchanges energy with the co-current passing particles with parallel velocity equaling to 1/3 or 1/5 of the Alfvén speed on the magnetic axis.**
- **Simulation of RMPs induced fast particle transport:**
  - **The loss fraction increases when the RMP coil current increases.**
  - **Without RMPs, the initial positions of lost fast ions are near the edge on the high field side. However, the initial positions of lost fast ions are located near the edge on both the low and high field side with RMPs.**

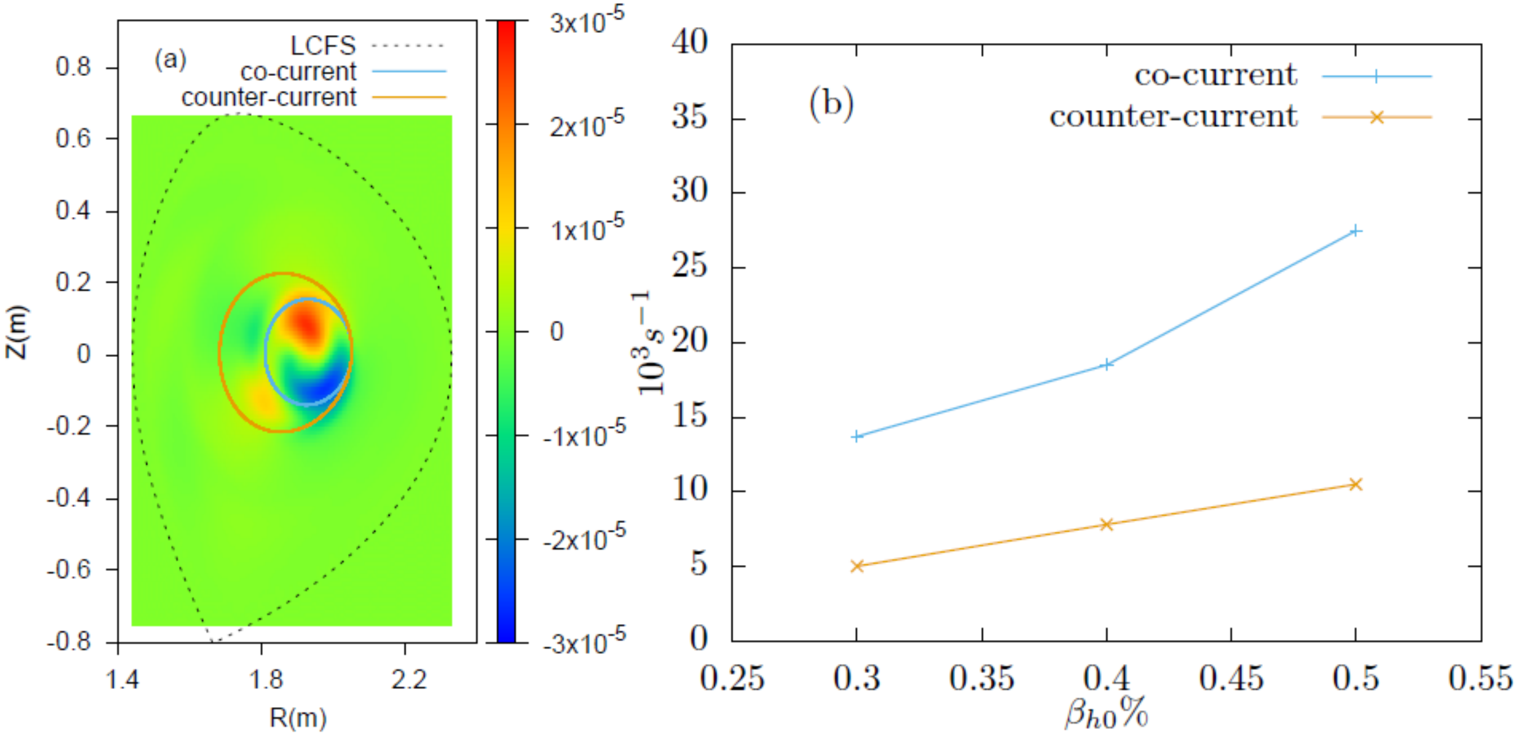
Thank you very much for your attention!

Large df structure is consistent with resonant condition

- (a) $P_{hot,0}/P_{total,0} = 0.25$: fishbone driven by lower energy
- (b) $P_{hot,0}/P_{total,0} = 0.4$: $\omega_{low} = \omega_\phi$ and $\omega_{high} = \omega_\phi + 2\omega_\theta$, double linear mode frequencies.
- (c) $P_{hot,0}/P_{total,0} = 0.5$: BAE driven by higher energy



TAE destabilized by counter-current passing fast ions is analyzed



- ➢ **the TAE destabilized by the counter-current passing ions has much smaller growth rate than that driven by the co-current ion.**

- **Possible explanation is that the overlapping region between the TAE and the co-current passing fast ions is larger than the counter-current passing fast ions.**