Energetic particle modes of q=1 high order harmonics in tokamak plasmas with monotonic weak magnetic shear

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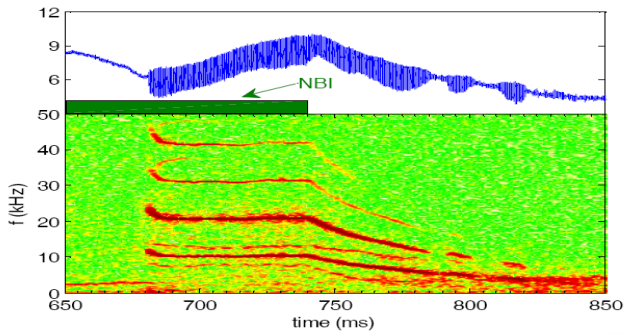
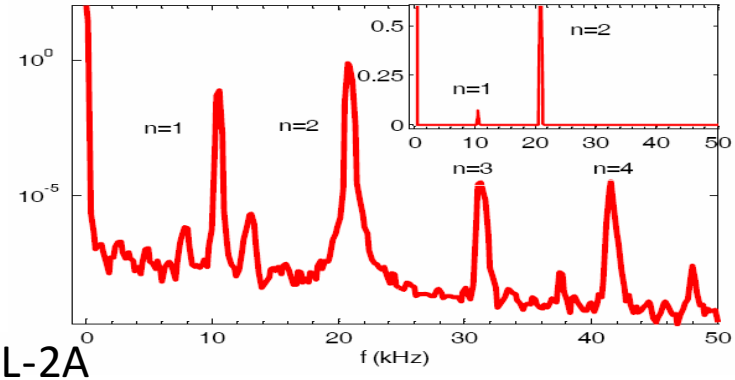
Outline

- **Background**
- **M3D-K model and basic parameters**
- **Linear results**
- **Nonlinear results**
- **Summary**

Background

- Energetic particle physics is a key issue in burning plasma experiments of advanced tokamaks, such as the International Thermonuclear Experimental Reactor (ITER).
- The weak magnetic shear is recommended for high-performance tokamak operations, since the flat q-profile in the core region can substantially eliminate the free energy of the current gradient, consequently prevent sawtooth crashes. However, some instabilities, such as long lived modes , ballooning and infernal, can be excited in the weak magnetic shear configuration.
- The phenomenon that the high order harmonics stronger than the n=1 component in the low magnetic shear have been observed in some devices, such as HL-2A





From HL-2A

Background

- Wang *et al* . numerically investigated the q-profile effect on high-order harmonics q=1 tearing mode during the sawtooth crash[1,2]. It is found that the q=1 high order harmonics can play crucial roles during the sawtooth oscillations and trigger the neoclassical tearing mode, which may lead to the disruption by supplying the seed island.

- However, the theoretical and numerical investigation of the q=1 high-order energetic particle modes has made little progress.

{1}.*Z. X. Wang, L. Wei, and X. G. Wang, Phys. Plasmas* ***19****, 062108 (2012).*

{2}.*L. Wei and Z. X. Wang, Phys. Plasmas* ***20****, 012512 (2013).*

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Physical model: M3D-K

Resistive MHD model:

$$\rho \frac{d\mathbf{v}}{dt} = \mathbf{J} \times \mathbf{B} - \nabla p + \mu \nabla^2 \mathbf{v}$$

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

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

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

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

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0$$

kinetic/MHD hybrid model:

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

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

$$P_\parallel(\mathbf{x}) = \int m v_\parallel^2 \delta(\mathbf{x} - \mathbf{X} - \rho_h) F(\mathbf{X}, v_\parallel, \mu) B^{\star\star} d^3\mathbf{X} dv_\parallel d\mu d\theta$$

$$P_\perp(\mathbf{x}) = \int \frac{1}{2} m v_\perp^2 \delta(\mathbf{x} - \mathbf{X} - \rho_h) F(\mathbf{X}, v_\parallel, \mu) B^{\star\star} d^3\mathbf{X} dv_\parallel d\mu d\theta$$

Gyrokinetic/drift-kinetic Equations:

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

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

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

$$B^{\star\star} = \mathbf{B}^\star \cdot \mathbf{b}_0$$

Basic parameters and initial profiles

Main parameters:

aspect ratio : R_0/a=3.6667.

elongation: K=1.0

triangularity: δ=0.0

central total beta: $\beta_{total,0} = 0.8\%$

central beam ion beta: $\beta_{hot} / \beta_{total} = 0.5$

Toroidal magnetic field: B_0=1.37T

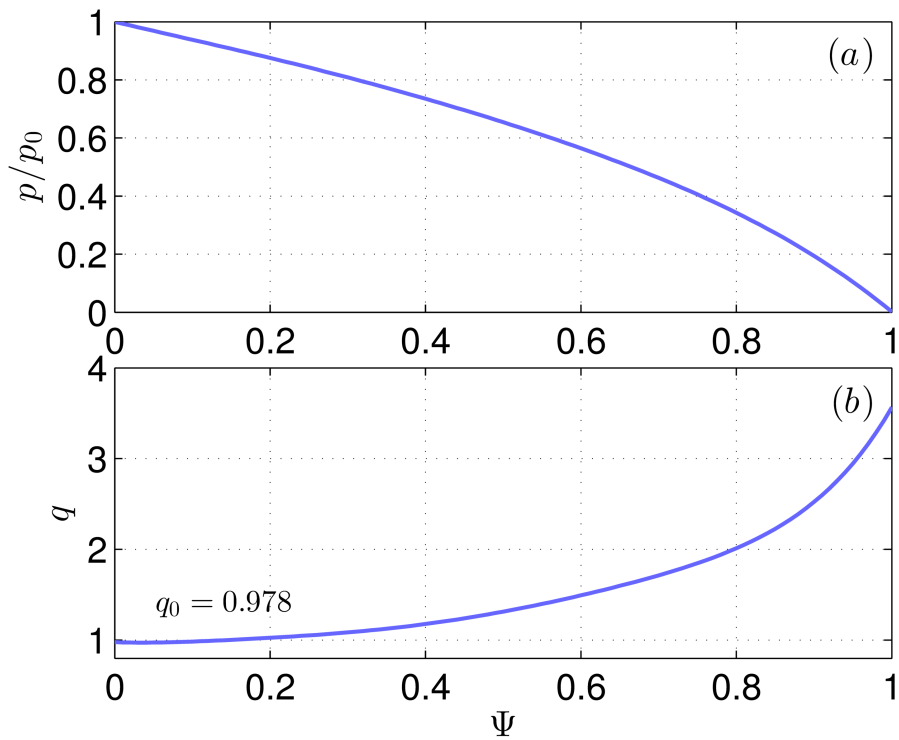
Beam ion distribution function:

$$f = \frac{cH(\upsilon_0 - \upsilon)}{\upsilon^3 + \upsilon_c^3} \exp(-(\Lambda - \Lambda_0)^2 / \Delta\Lambda^2) \exp(-\langle\Psi\rangle / \Delta\Psi)$$

$\Lambda \equiv \mu B_0 / E$ Λ=1.0, $\Delta\Lambda$=0.1, $\Delta\Psi$=0.3

The normalized beam particle speed and gyroradius are given by:

$$\nu_h / \nu_A = 0.3966, \rho_h / a = 0.0645$$



Equilibrium profiles of pressure and safety factor . And the plasma density profile is uniform in space.

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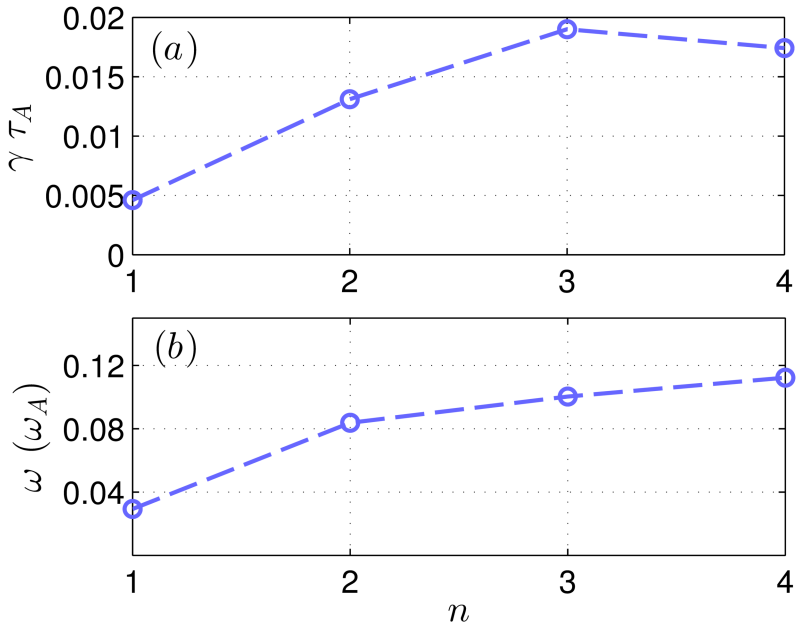
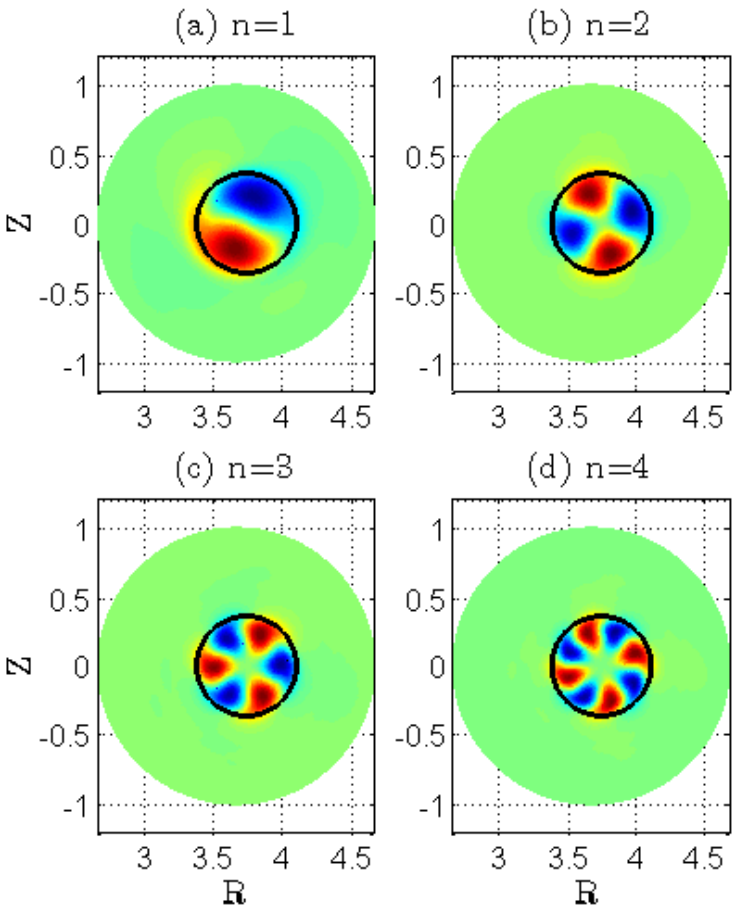
Linear results



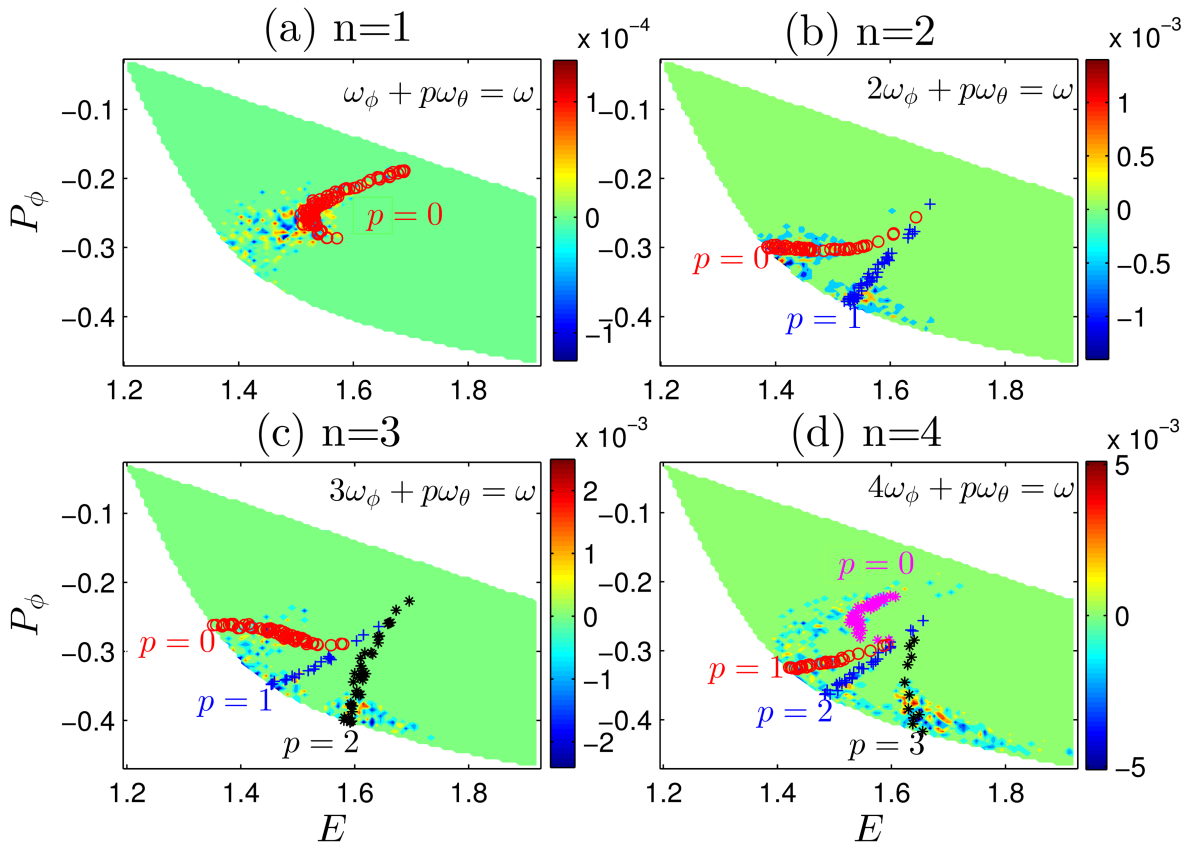
- It is found that the mode is stable in the MHD limit. Furthermore, it is observed that when the kinetic effects of beam ions are included, the high-order harmonics have a larger growth rate than the m/n=1/1 harmonic.



Linear mode structure(stream function U)

The solid line shows the q=1 surface location.

Linear results: resonant condition analysis

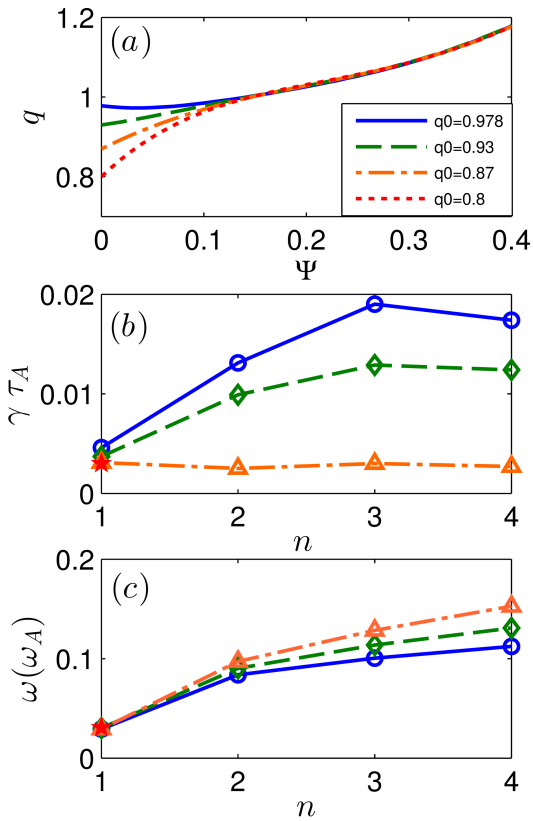


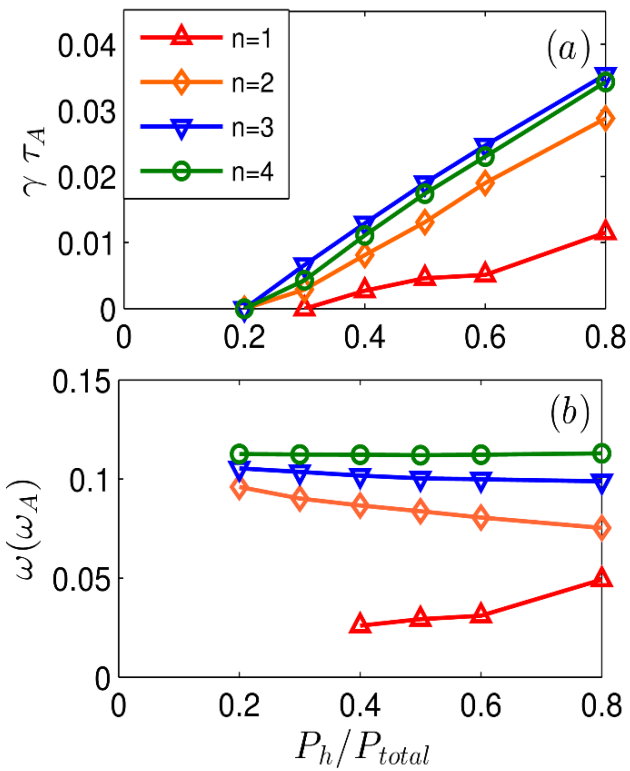
- For the high-order harmonics, they satisfy multiple resonant conditions, while the n=1 component has only one resonant condition, which are quite different from the typical fishbone instability.

Linear results

Excitation conditions of high-order harmonics

- For a flat q-profile in the core region, the high order harmonics modes can be excited.
- Each mode is excited when the fast ion pressure exceeds a threshold, which indicates that energetic trapped particles play an essential role for the destabilization.





- The high-order harmonics stronger than the m/n=1/1 mode can be excited in low magnetic shear with a higher beam ion pressure.

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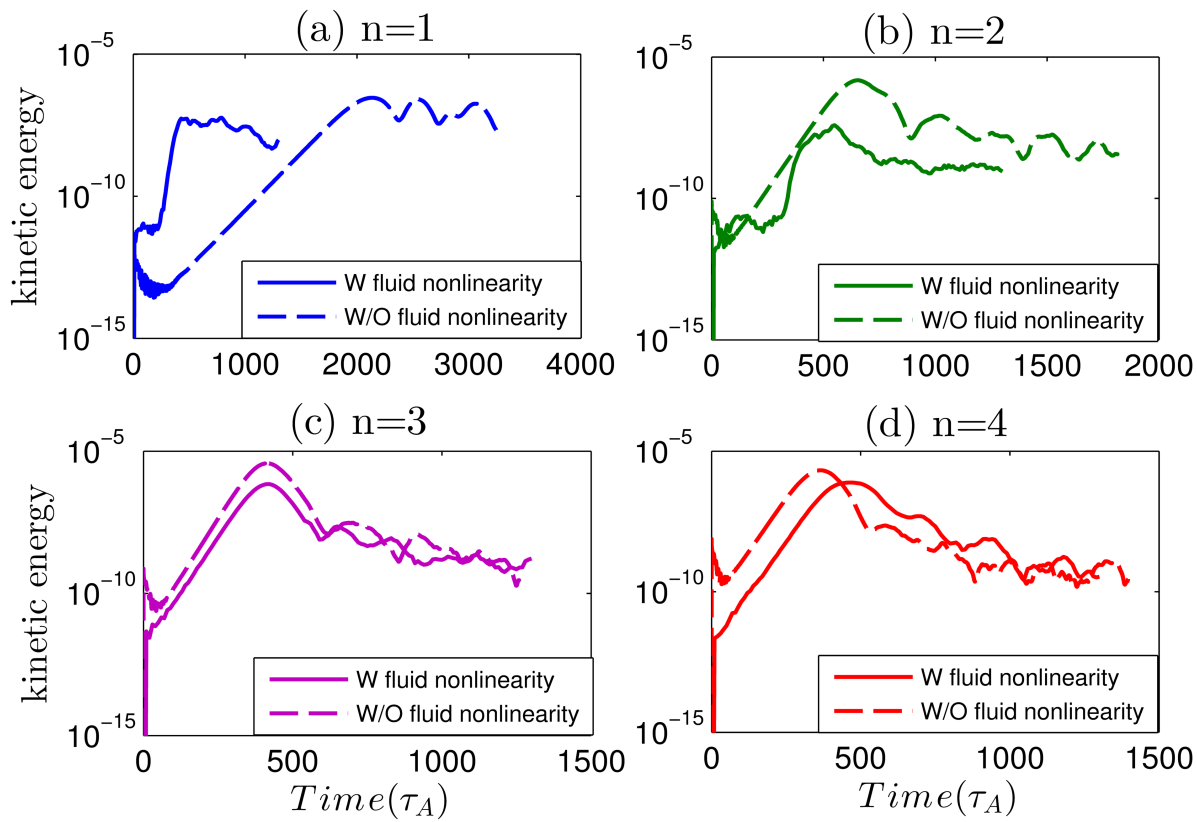
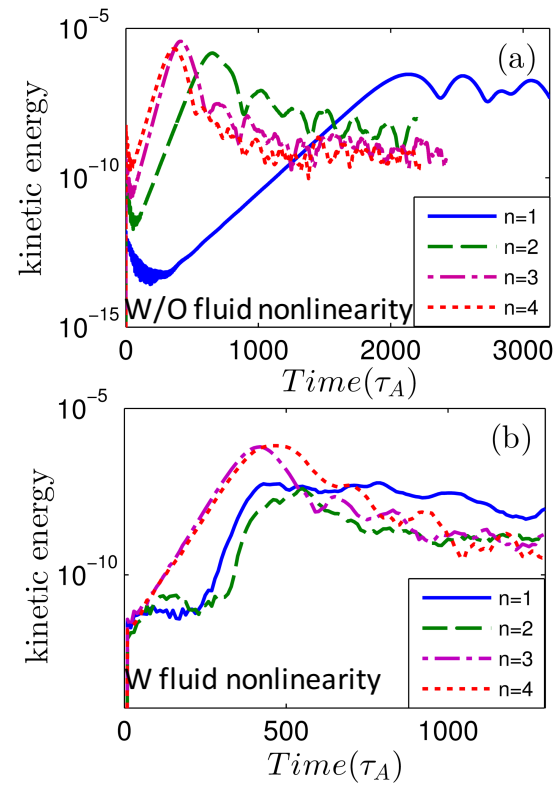
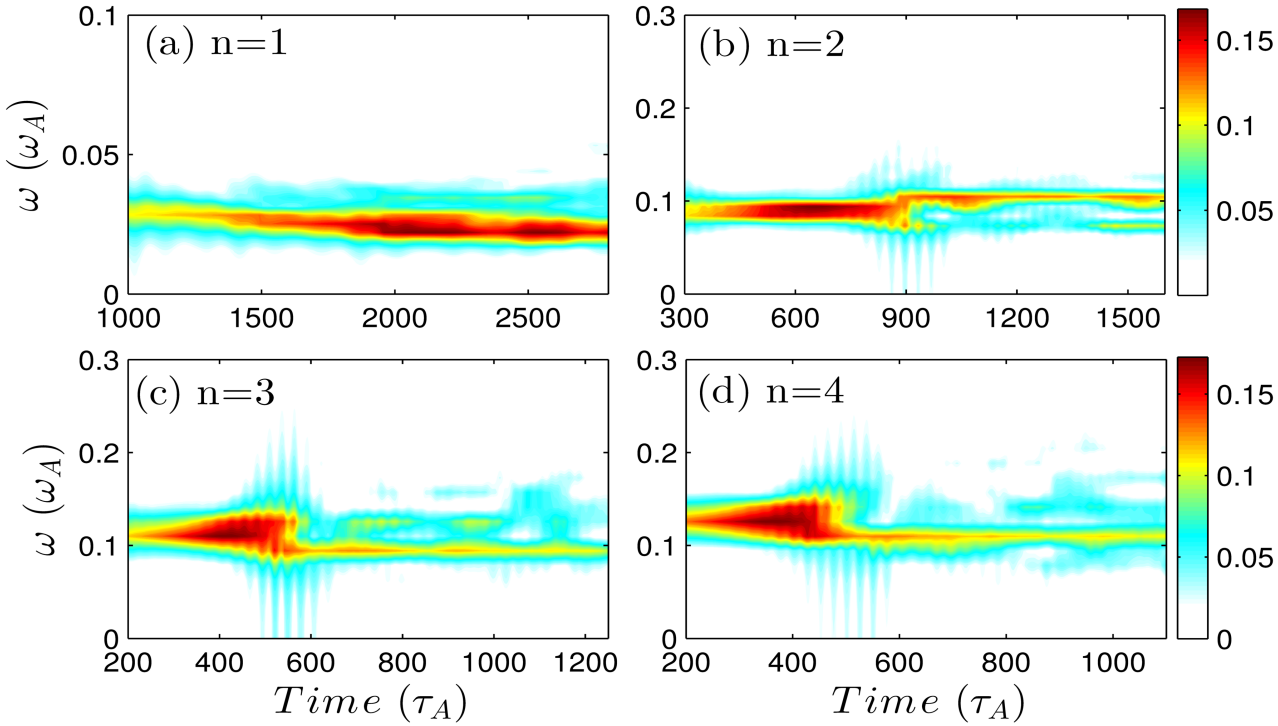
Nonlinear results: fluid nonlinearity effect





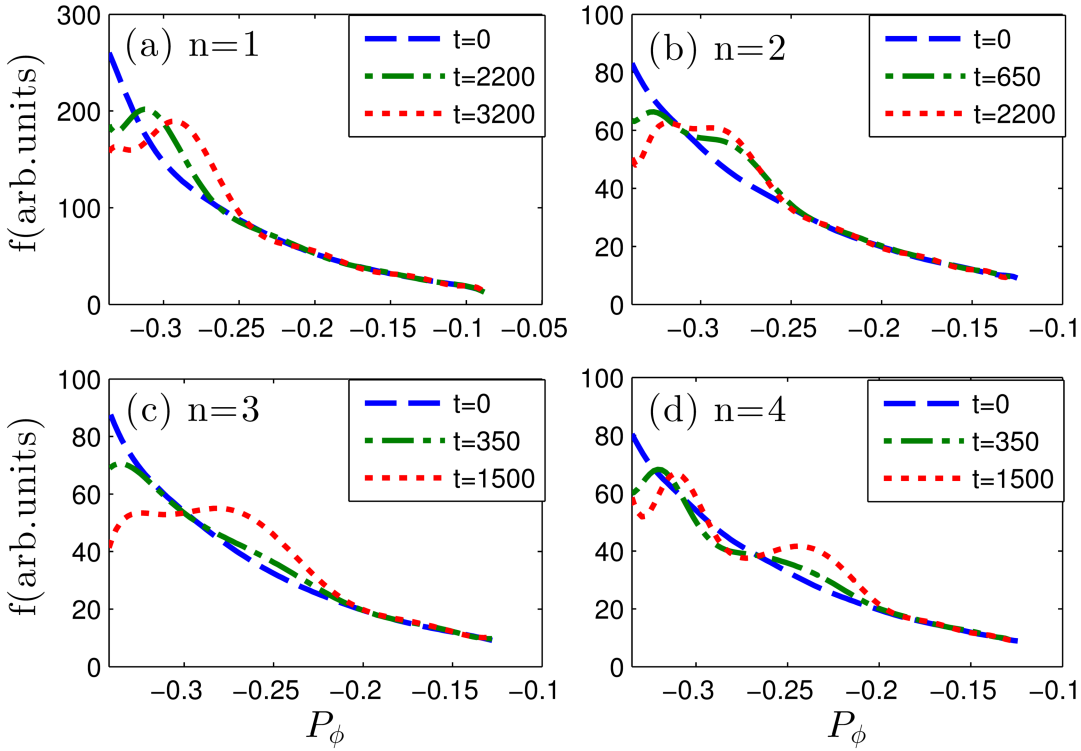
- The fluid nonlinearity reduces the saturation level of the m/n=1/1 component, while it hardly affects high-n components, especially the modes with m=n=3,4.
- The maximum values of kinetic energy of high-order harmonics are all larger than m/n=1/1, while the m/n=1/1 mode is dominant in the saturated phase.

Nonlinear results: mode frequency evolution



- n=1: the frequency chirps down continuously
- n=2: the frequency firstly stays almost unchanged, and then shifts upward about 10% and later keeps constant again afterwards.
- n=3 and n=4: the frequencies firstly keep almost constant values, and then shift downward about 10% , and then keep constant again with time.

Nonlinear results: 1D distribution of fast ions

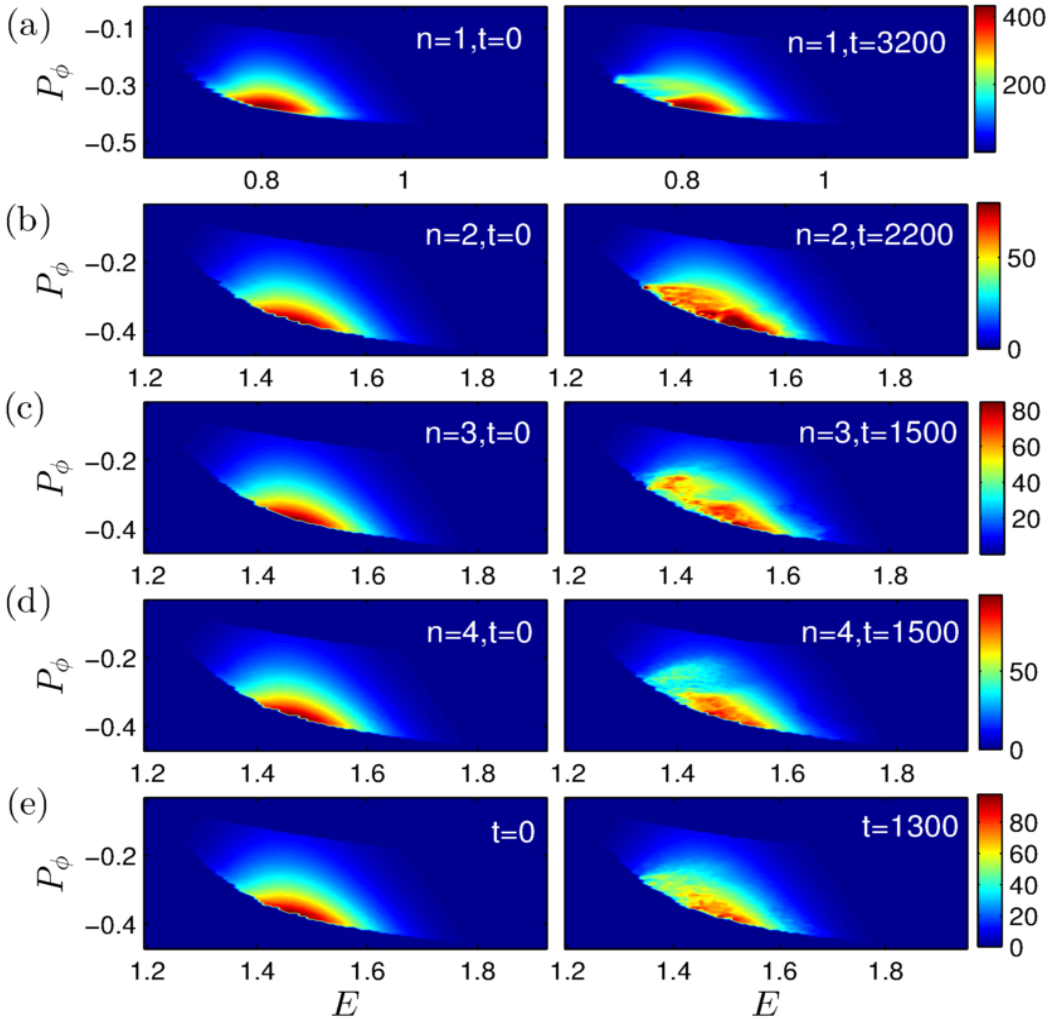


n=1 with μ~0.8 and E=0.76; n=2,3, 4 with μ~1.5 and E=1.43.

- The flattening region of energetic particle distribution function due to separately high order harmonics excitation is wider than that due to m/n=1/1 component.

Nonlinear results: 2D distribution of fast ions

- In comparison with the n=1 component, there is a larger flattening region of distribution function for the high-order harmonics.
- When fluid nonlinearity is included, the flattening region is larger than that without fluid nonlinearity.



Summary and Perspectives

- **Linear results:**
  - For a flat q profile in the core region, the linear growth rate of high order harmonics driven by energetic trapped particles can be higher than the n=1 component.
  - There exist multiple resonant locations satisfying different resonant conditions in the phase space of energetic particles for the high n components.
- **Nonlinear results:**
  - The fluid nonlinearity reduces the saturation level of the n=1 component, while it hardly affects high n components.
  - The flattening region of energetic particle distribution due to high-order harmonics excitation is wider than that due to n=1 component, although the n=1 component has higher saturation amplitude.
- **The mechanism of high order harmonic modes driven by passing energetic particles in the weak magnetic shear configuration will be considered in future.**

Thank you for your attention!