# Nonlinear excitation of energetic particle driven geodesic acoustic mode via resonance overlap in CFQS

*Presenter:* **Hao WANG**
*Collaborators:* Zhe CHEN, Haijun REN, Yasushi TODO, Jiangyue HAN, and Jialei WANG

核融合科学研究所　成果報告会
岐阜県土岐市
２０２６年6月１５日〜１６日

# Content

# Introduction

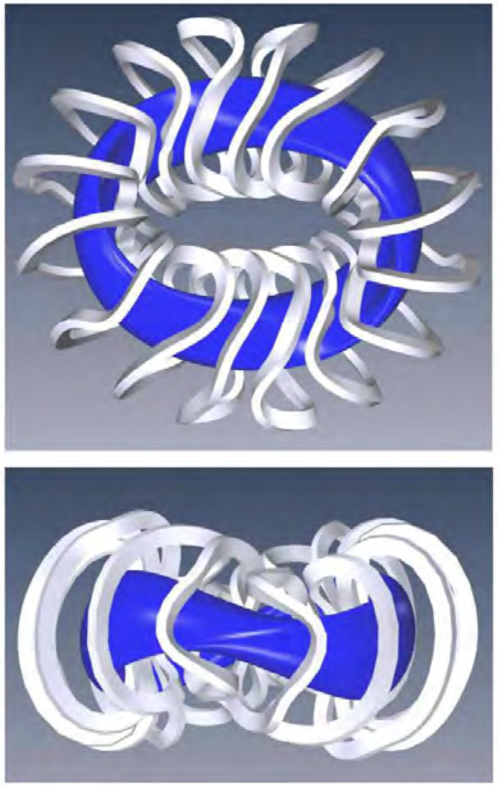
## Chinese First Quasi-axisymmetric Stellarator (CFQS)

- International Joint Program between National Institute for Fusion Science (Japan) and Southwest Jiaotong University (China)

- Quasi-axisymmetric (**QA**) Stellarator (tokamak-like stellarator)
  - good for reducing neoclassical transport
  - good for steady state operation

- **Energetic particles (EPs) driven instabilities** are simulated in CFQS. A novel **nonlinear excitation mechanism** will be presented in this work.

[Zhe Chen *et al* 2026 Nucl. Fusion 66 014003]



[M. Isobe *et al* 2019 Plasma and Fusion Research, 14 3402074.]

# Content

# MEGA code is applied for CFQS simulation

**MEGA** **[Y. Todo, Physics of Plasmas, 2006. 13 082503]**

A hybrid simulation code for EPs interacting with a magneto-hydrodynamic (MHD) fluid.

## Basic Parameters

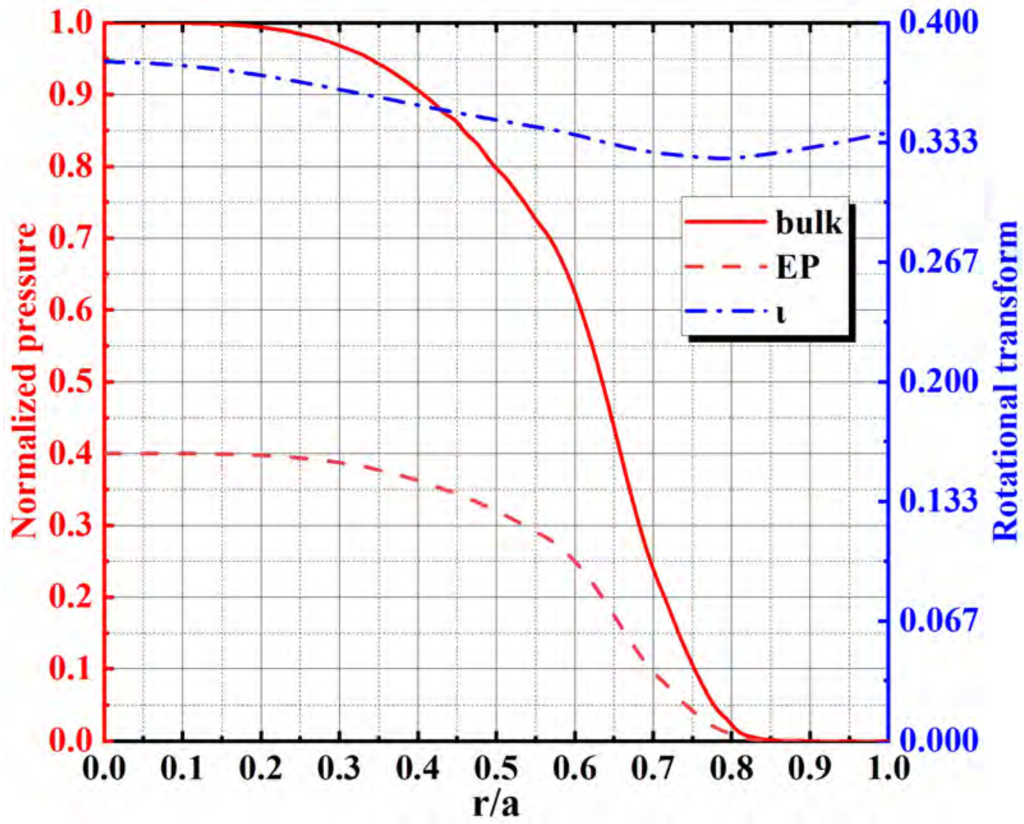
- Major radius: $R_0 = 1.0\text{m}$
- Magnetic field on axis: $B_0 = 1.0\ T$
- Central electron density: $n_e = 1.0 \times 10^{19}\ m^{-3}$
- Central electron temperature: $T_e = 2.1\ \text{ke}V$
- Core region $\beta_{bulk}$: $\beta_{bulk} = 1.0\%$
- Plasma species: Hydrogen
- Field period number: $\boldsymbol{N_{FP} = 2}$

## EP Parameters

- NBI energy: $E_{NBI} = 40keV$
- Core region $\beta_{EP}$: $\beta_{ep} = 0.4\%$
- EP distribution: anisotropic slowing-down distribution
- Gaussian-type pitch angle variable $\Lambda$ distribution:

$$f(\Lambda) = \exp\left[-\frac{(\Lambda - \Lambda_0\ \ )^2}{\Delta\Lambda^2}\right] \quad \text{with } \Lambda = \frac{v_\perp^2 B_{axi}}{v^2 B},\ \Lambda_0 = 0.4$$

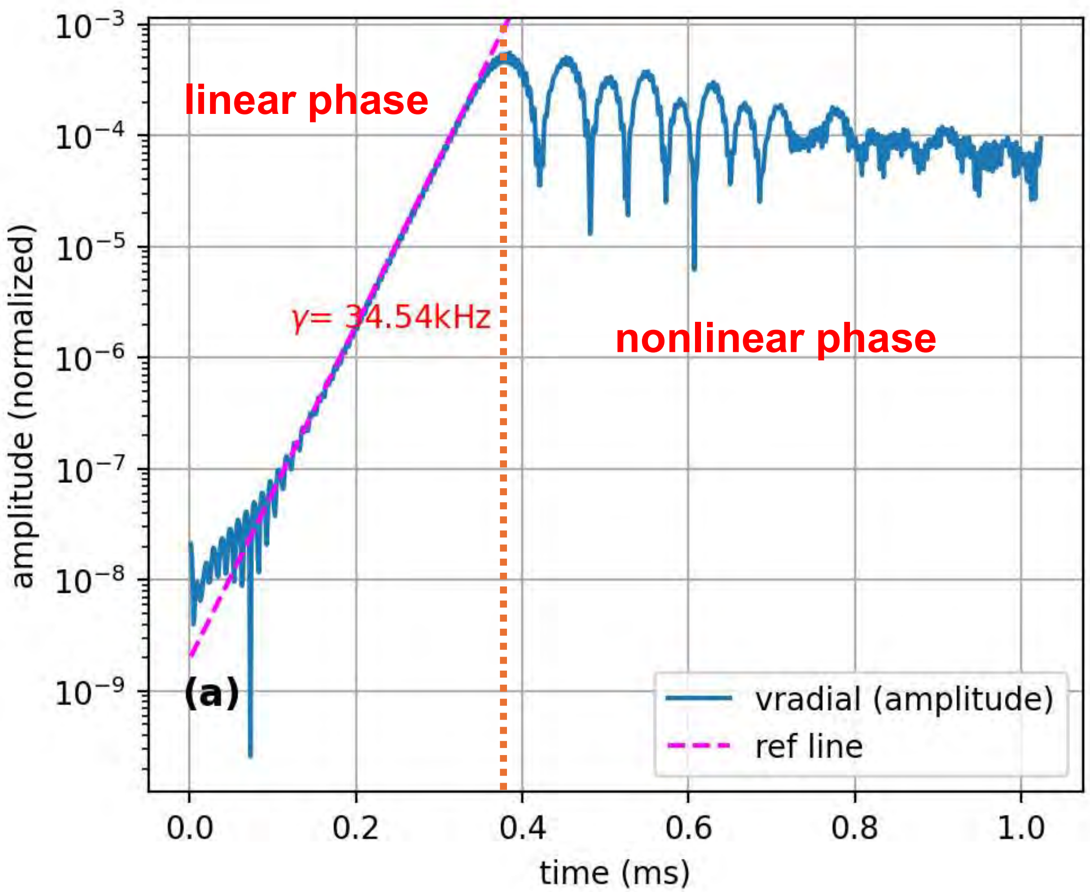
[Hao Wang *et al* 2022 *Nucl. Fusion* **62** 106010]




Profile of equilibrium pressure and rotational transform $\iota$, created by HINT.

# Time evolution of $v_{r,m/n=6/2}$

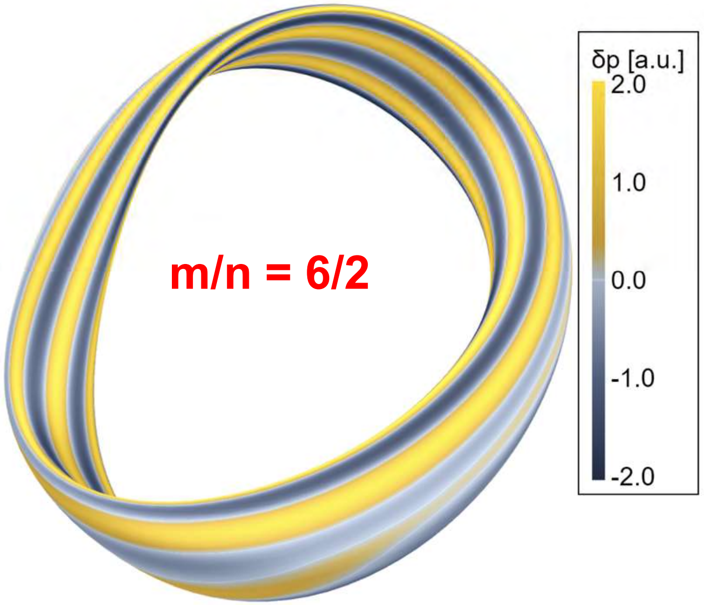
Dominant velocity component in linear phase is $v_{r,m/n=6/2}$




- Linear phase ends at $t\sim 0.4$ms.
- Identified as energetic-particle-mode (EPM).
- In the nonlinear phase, the amplitude of $\boldsymbol{v}_{r,m/n=6/2}$ basically decreases.
- Actually, **another instability appears and becomes dominant** in the nonlinear phase.

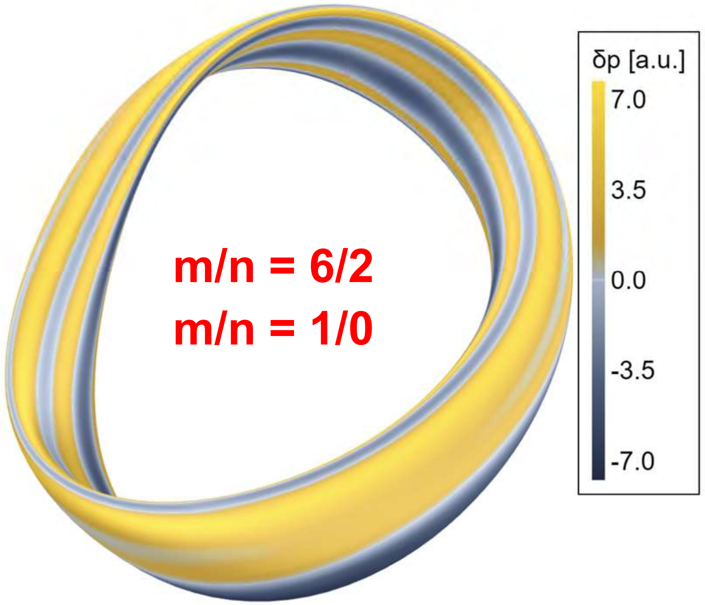
# Pressure perturbation *[Cover image, 1st issue, Nuclear Fusion 2026]*

**linear phase**
t = 0.31ms



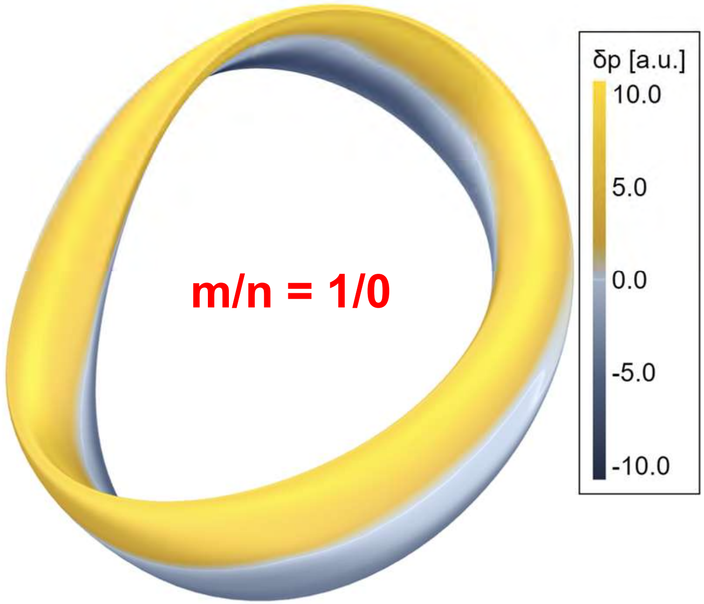

EPM
(energetic-particle-mode)

**nonlinear phase**
t = 0.62ms




EPM
EGAM

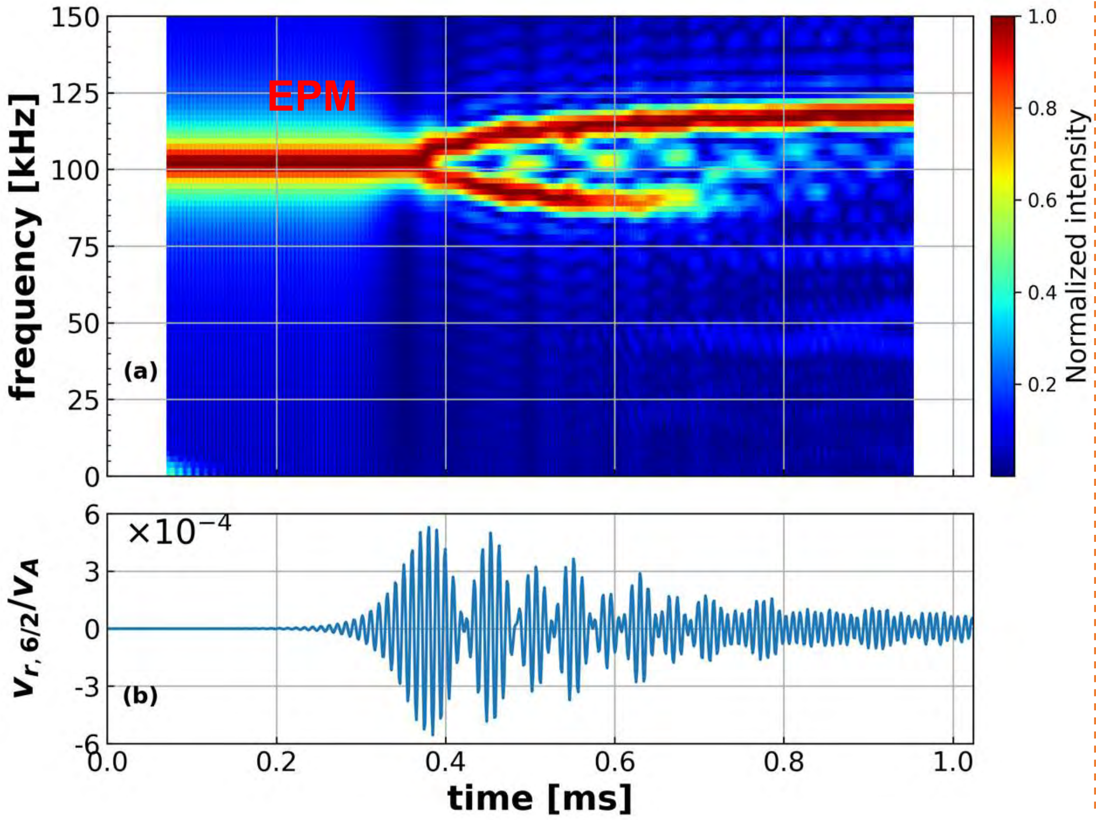
**nonlinear phase**
t = 0.85ms



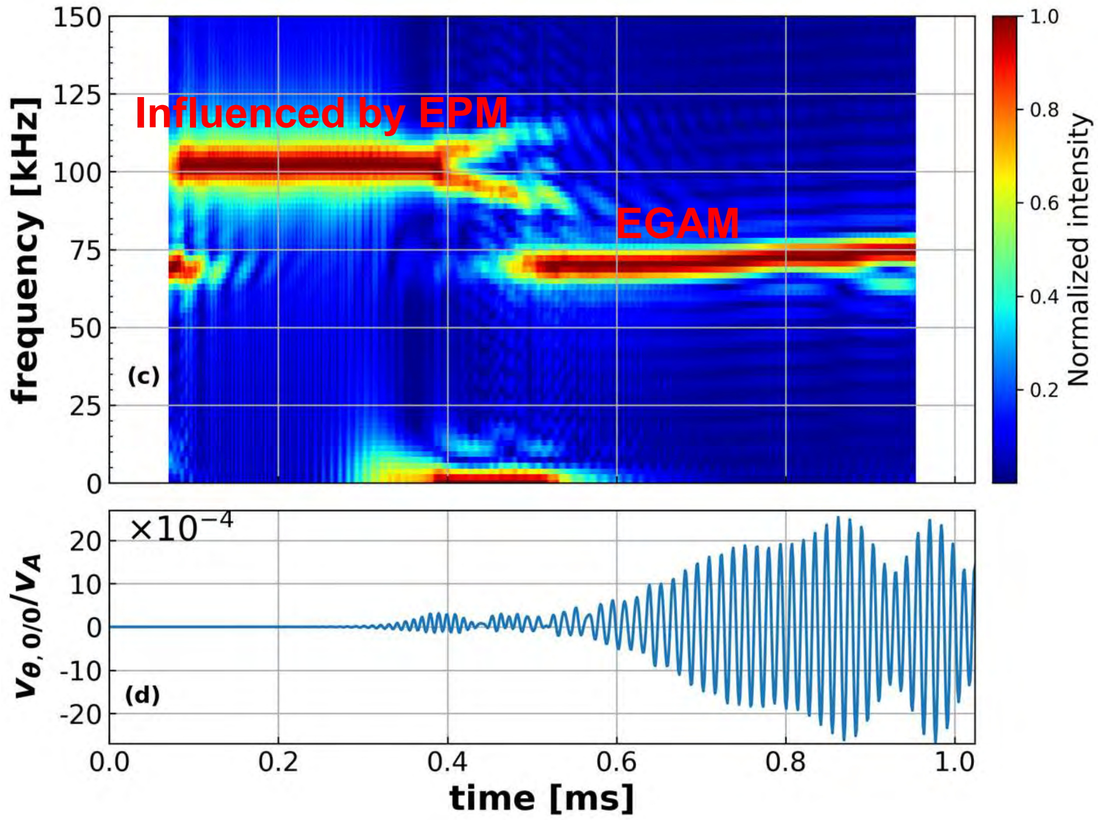

EGAM
(energetic particle driven
geodesic acoustic mode)

# Frequency spectrum

$v_{r,m/n=6/2}$ dominant velocity component for **EPM**



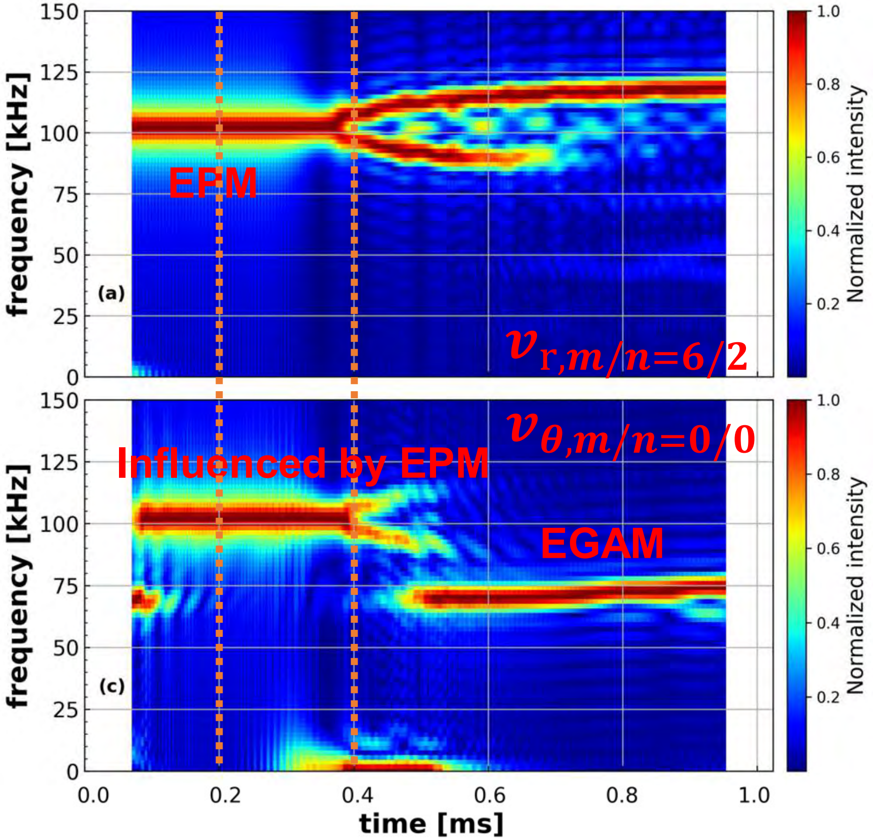

$v_{\theta,m/n=0/0}$ dominant velocity component for **EGAM**

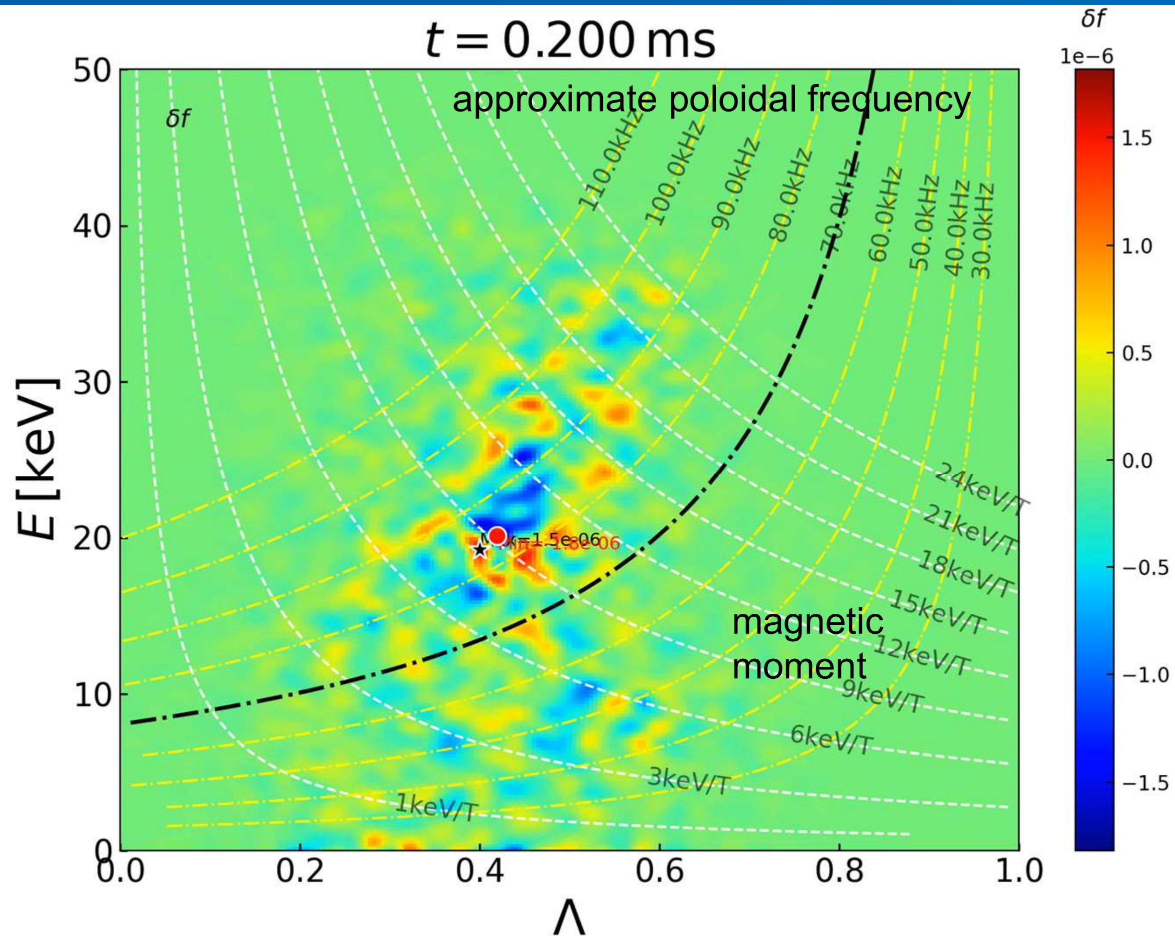



- EPM frequency ~ 100kHz in linear phase; EPM splits into two branches in nonlinear phase.
- **EGAM appears after EPM chirping for ~0.1ms.**

**Nonlinear excitation mechanism?**

# EP nonlinearity: resonance overlap (stage I)



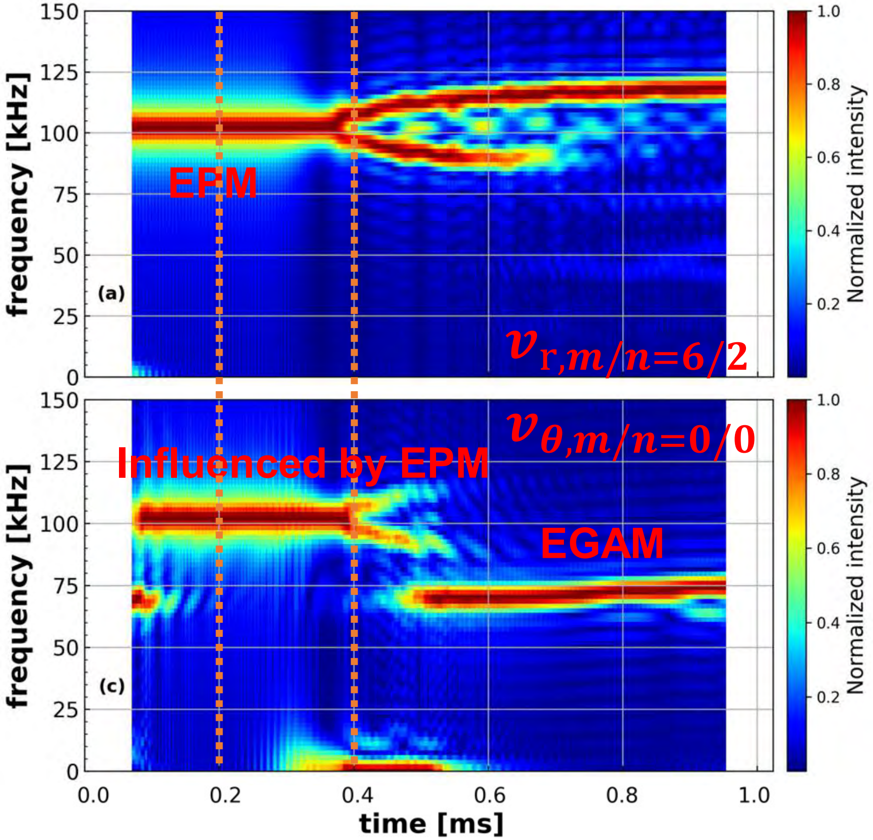



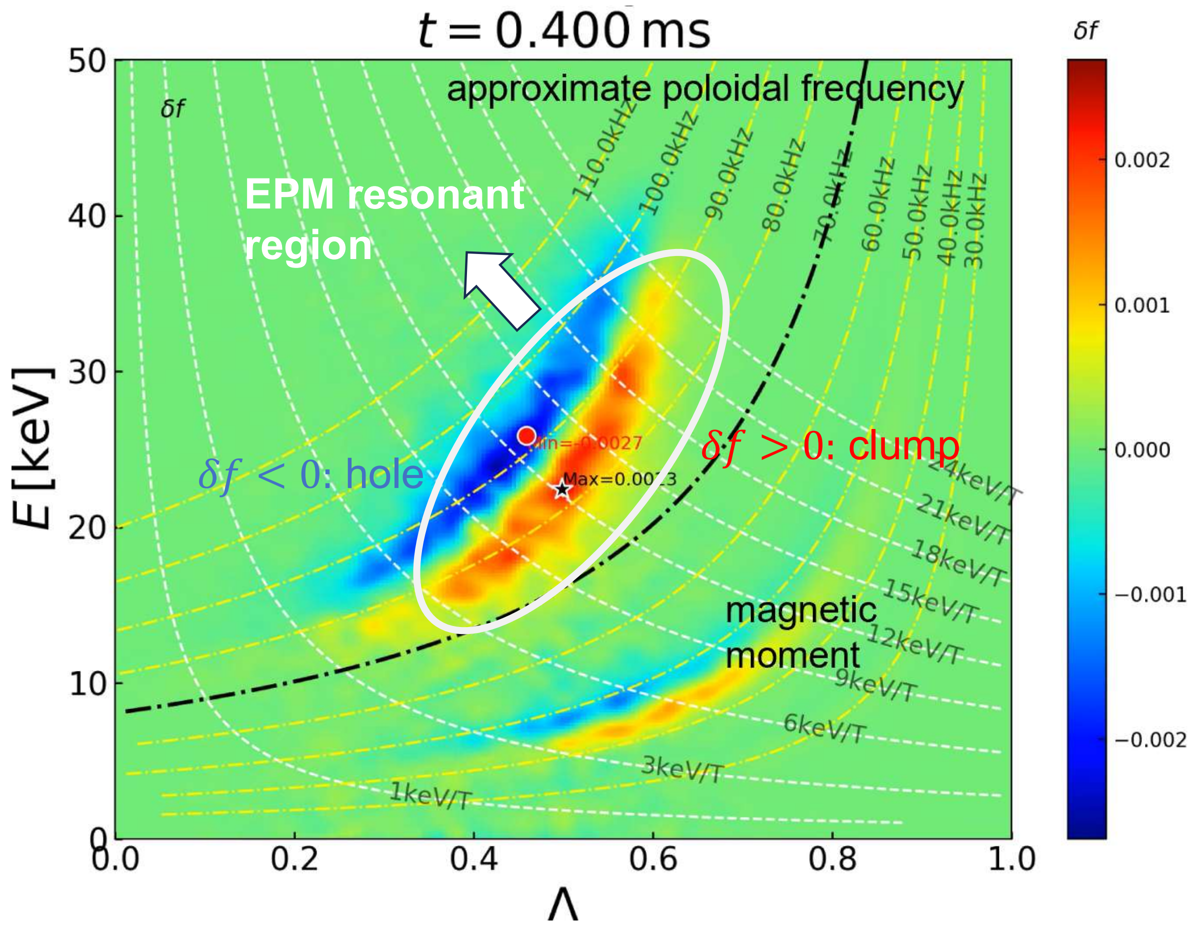

**Stage I**(0.2-0.4ms): linear stage

- EPM linearly grows. Hole-clump structures are gradually formed.

Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap (stage I)



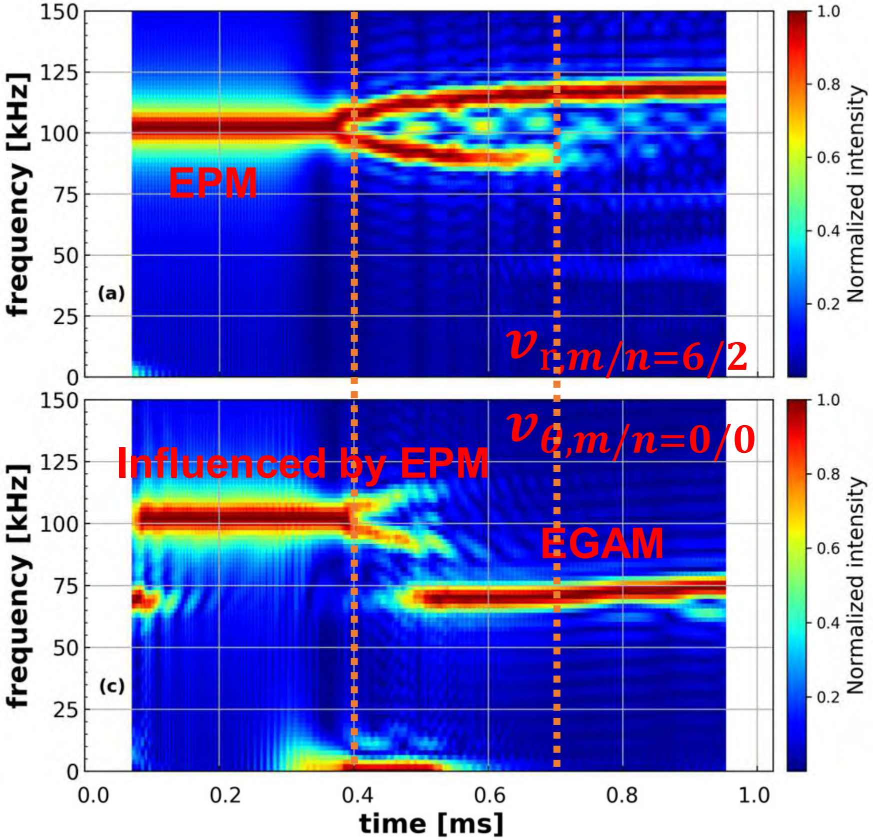



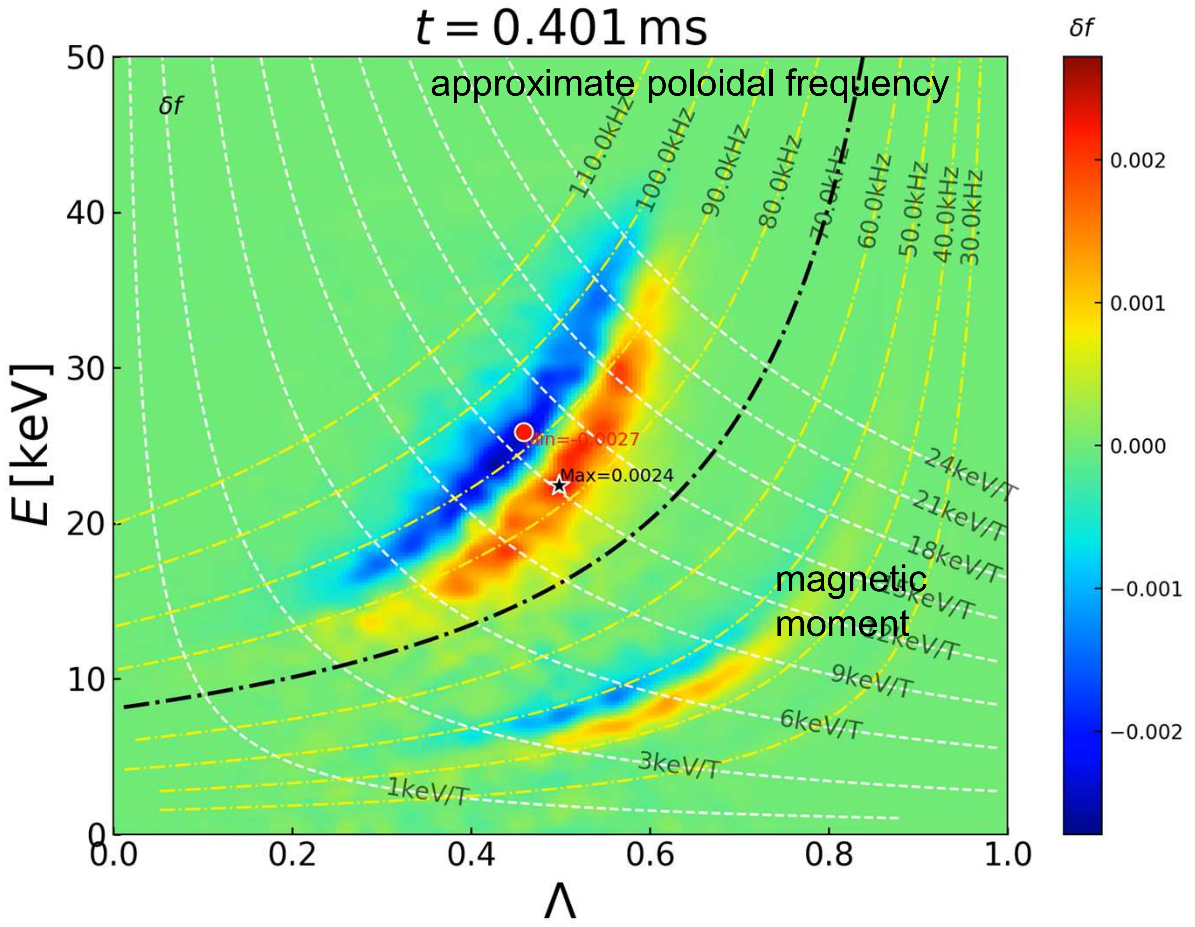

**Stage I**(0.2-0.4ms): linear stage

- EPM linearly grows. Hole-clump structures are gradually formed.

Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap (stage Ⅱ)



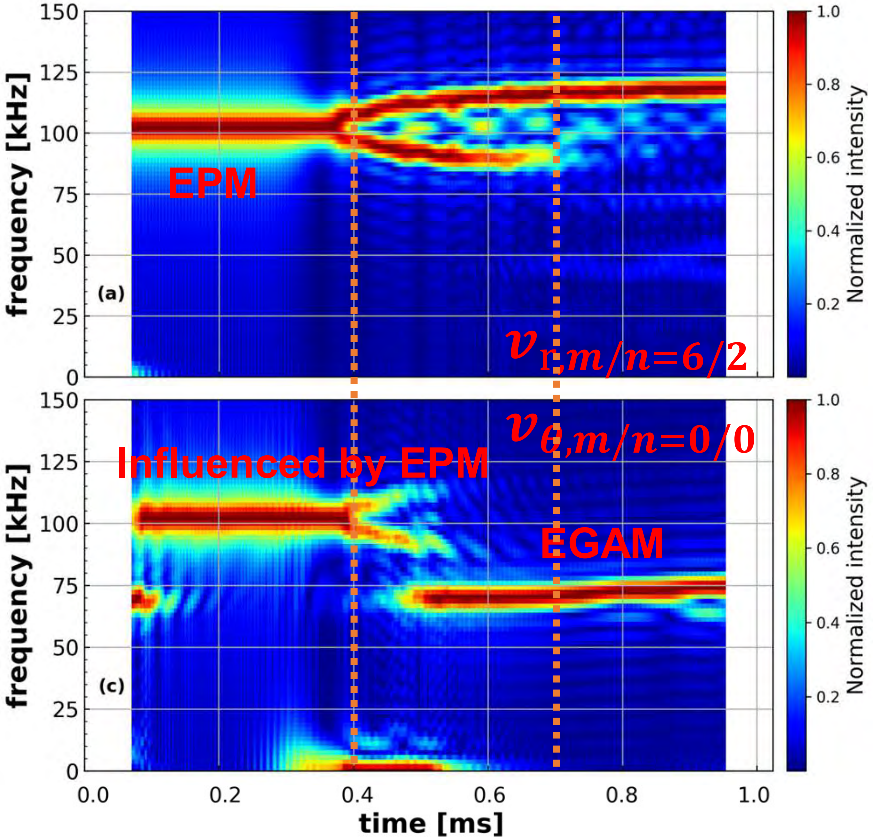



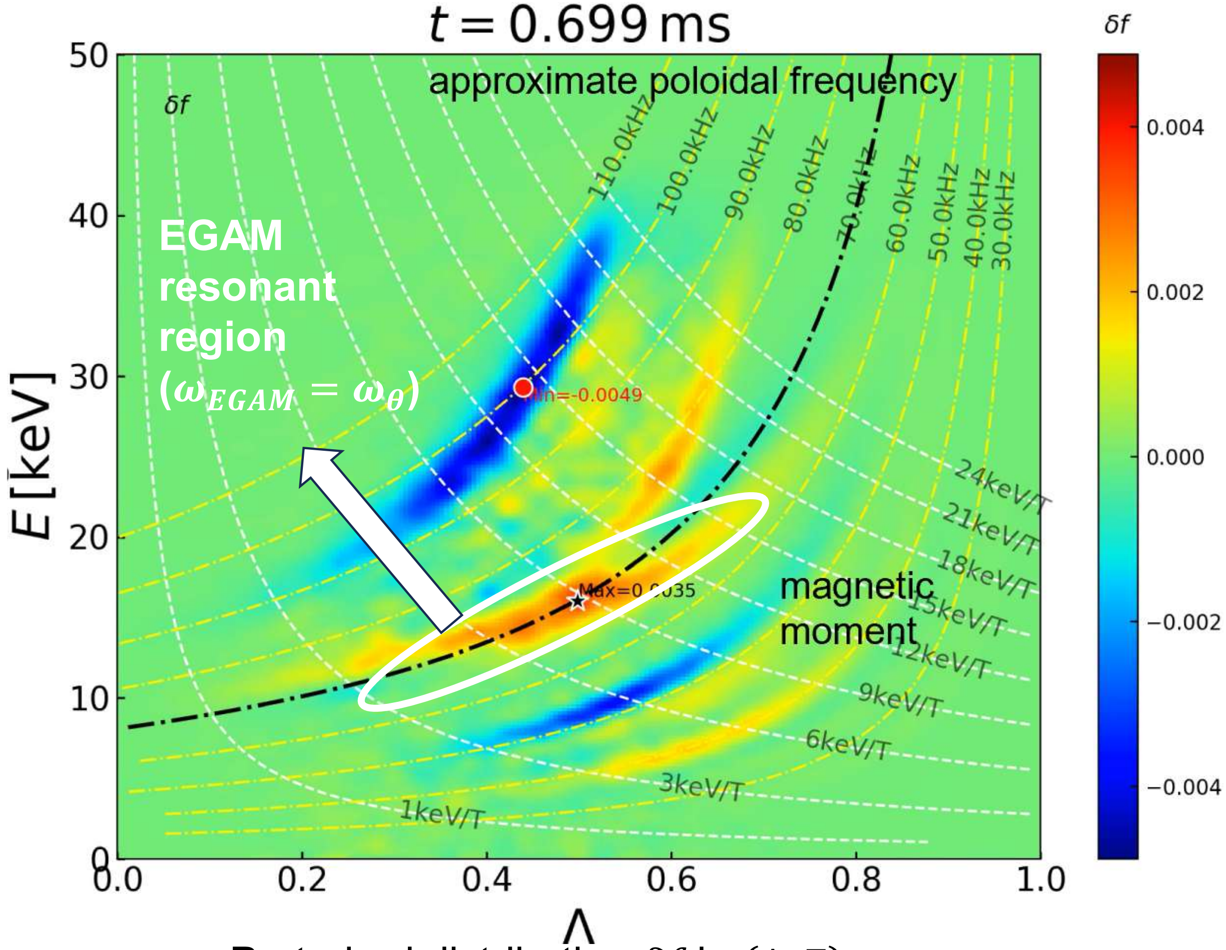

**Stage Ⅱ** (0.4-0.7ms): nonlinear stage

- EPM splits into two branches with chirping, corresponding to the motion of hole and clump.
- EGAM appears at $t \approx 0.5$ms.

Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap (stage Ⅱ)



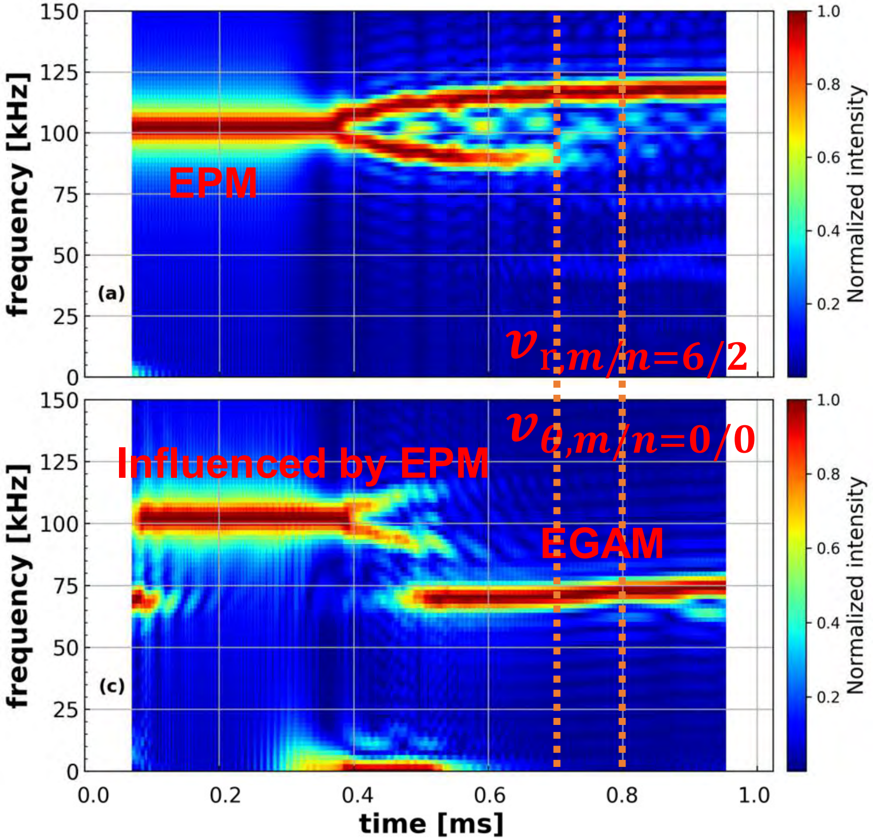




**Stage Ⅱ** (0.4-0.7ms): nonlinear stage

- EPM splits into two branches with chirping, corresponding to the motion of hole and clump.
- EGAM appears at $t \approx 0.5$ms.

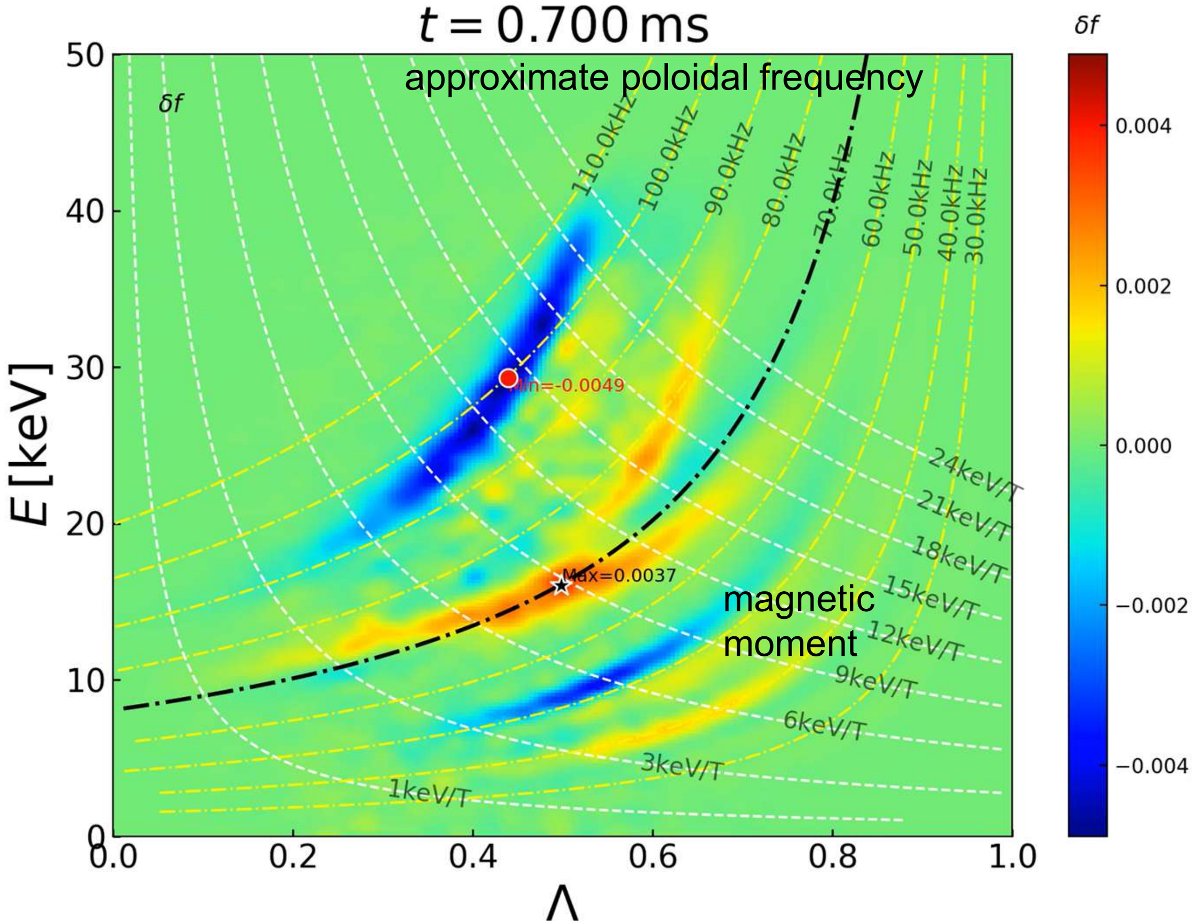
Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap (stage Ⅲ)



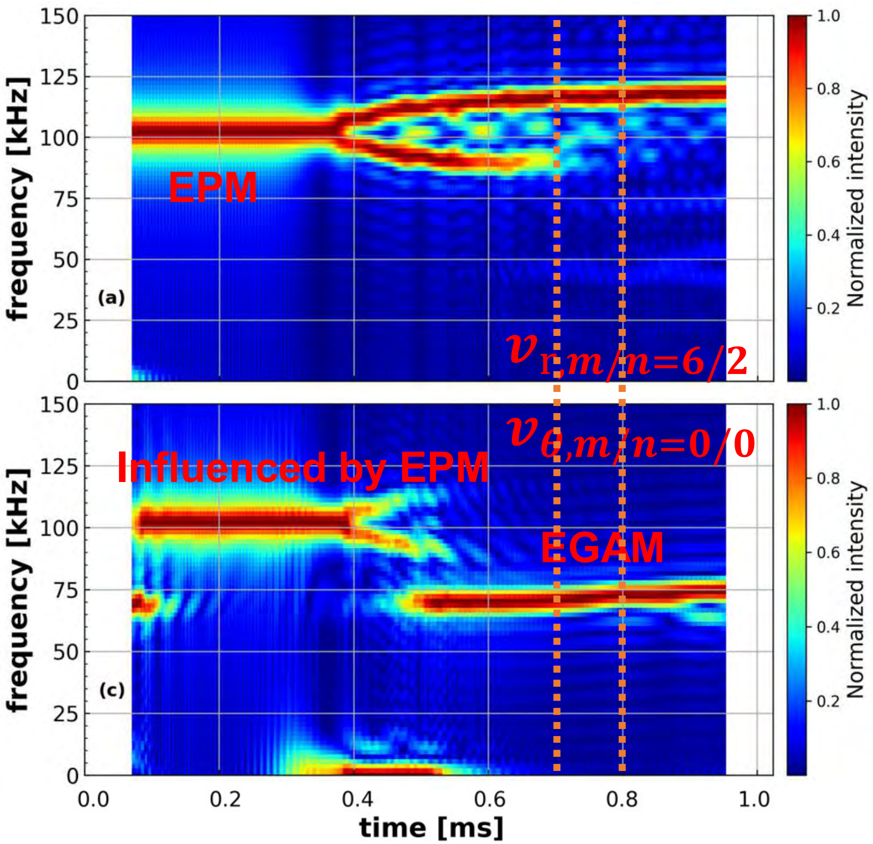

**Stage Ⅲ** (0.7-0.8ms): nonlinear stage

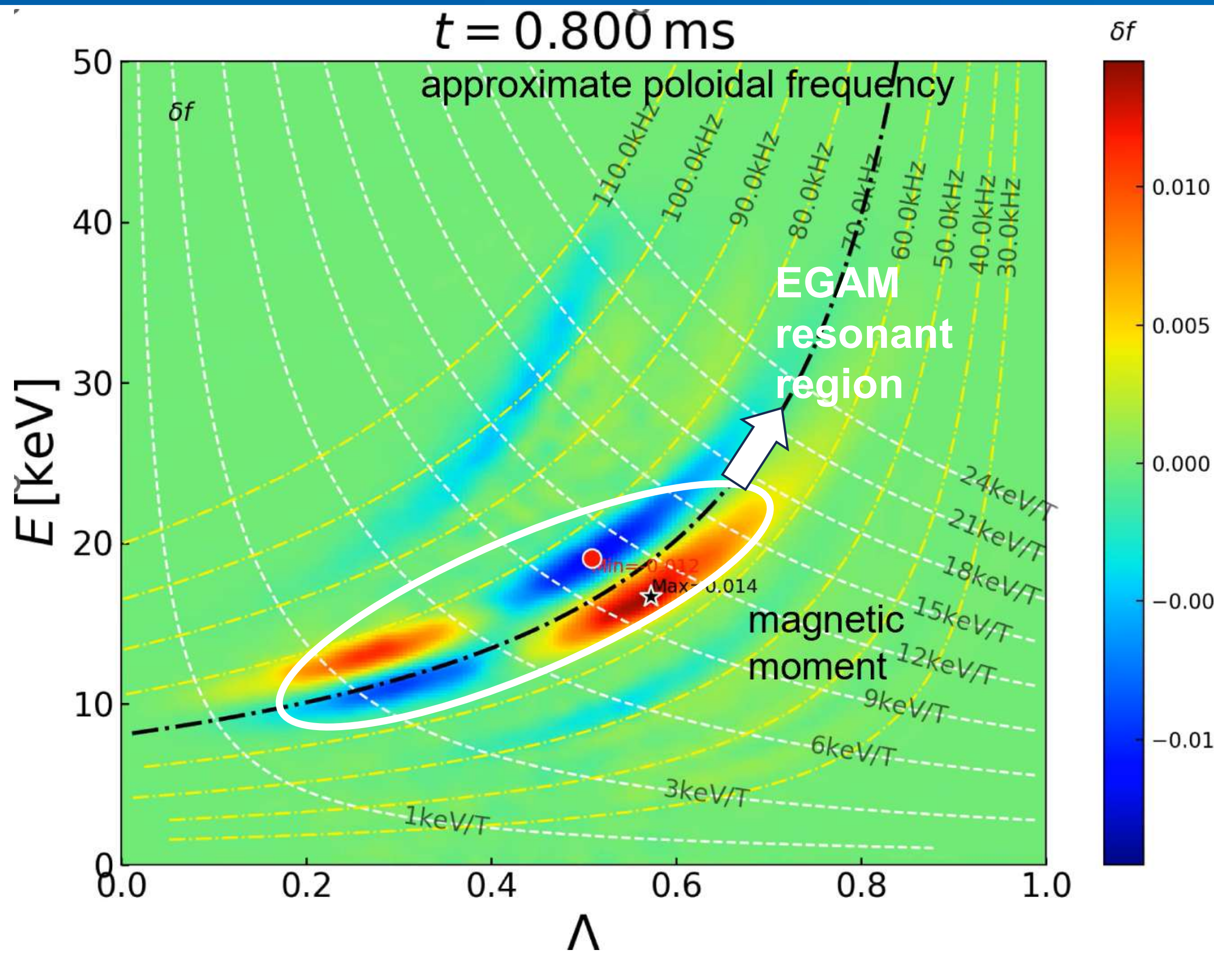
- EPM low-frequency branch disappears; the original dominant clump disappears.




Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap (stage Ⅲ)



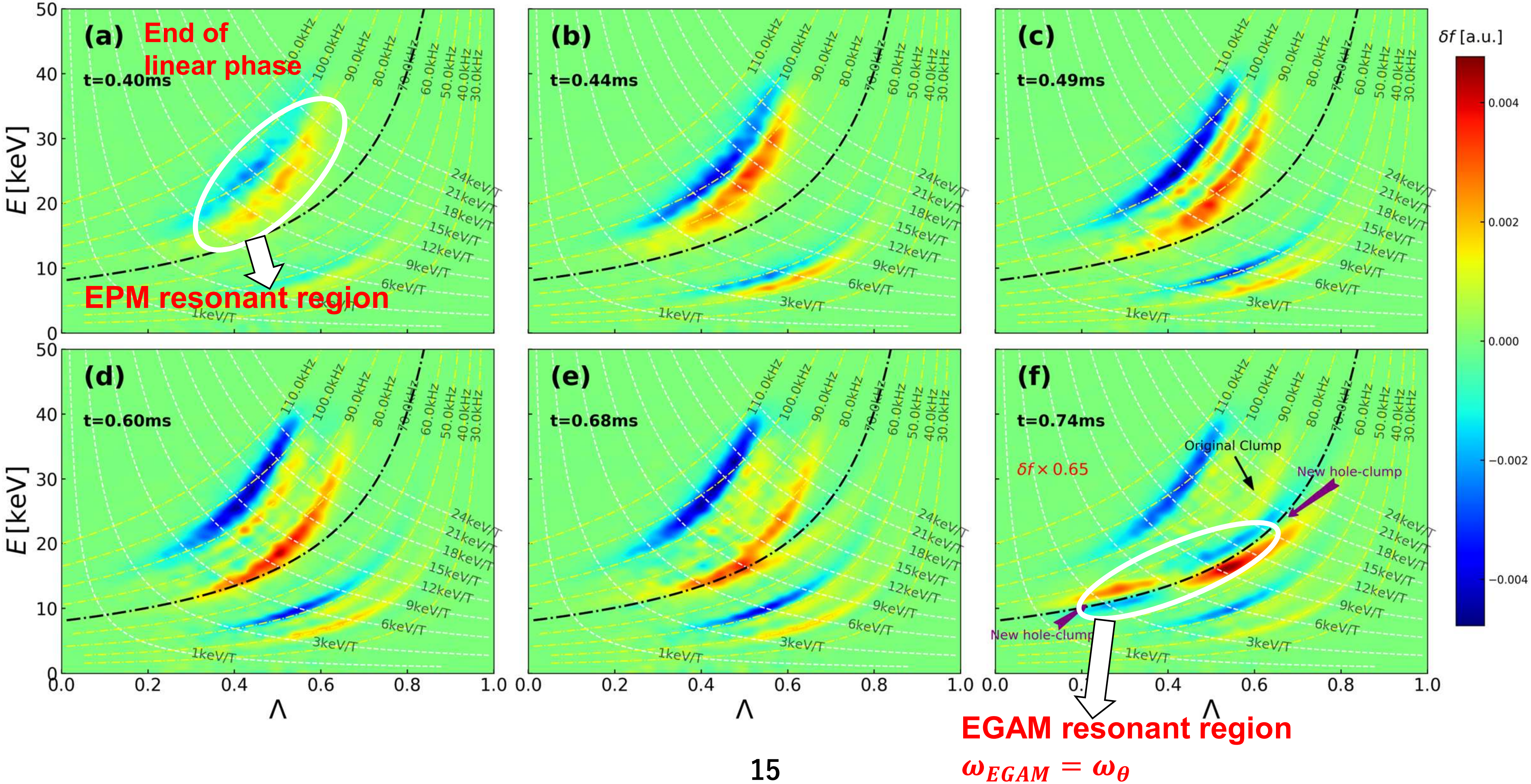




**Stage Ⅲ** (0.7-0.8ms): nonlinear stage

- EPM low-frequency branch disappears; the original dominant clump disappears.

Perturbed distribution $\delta f$ in $(\Lambda, E)$ space.
$\delta f > 0$: clump; $\delta f < 0$: hole;

# EP nonlinearity: resonance overlap



# Content

# Summary

**Simulation results of EP-driven instability in CFQS:**

- **Linear phase**:
  - **6/2 EPM** (~ $100$ kHz) is the dominant linear instability.
- **Nonlinear phase**:
  - 6/2 EPM splits into 2 branches, with frequency chirping up and chirping down.
  - An **EGAM** (~ $70$ kHz) is excited in nonlinear phase.
- **Nonlinear excitation mechanism of EGAM—resonance overlap**:
  - In linear phase, hole–clump structures of $\delta f$ gradually form in $(\Lambda, E)$ space.
  - In nonlinear phase, during the chirping of EPM, **one clump gradually moves towards the EGAM resonance region**, triggering EGAM nonlinear excitation.

Thanks for your attention!