Simulation analysis of reversed shear Alfvén eigenmode dynamics and energetic particle transport during current ramp-up *

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The general property of RSAE is well-known

- Routinely observed during plasma current ramp-up with external heating.
- Mostly upward sweeping frequency following $q_{\text{min}}$ evolution.
- Very useful for MHD spectroscopy.

JET, ICRH heating, magnetic signal
More remains to be understood when strongly driven

- (fishbone-like) fast frequency chirping with much slower sweeping
- RSAE’s impact to EP distribution raises a crucial question.

This talk: proof-of-principle simplified hybrid simulation analysis.

- to verify: fast chirping induced by EPs’ “non-perturbative” effect.

JT-60U, N-NBI heating, magnetic signal
Shinohara et al. Nucl. Fusion 41, 603 (2001)
Outline*

1. Code model and assumptions
2. Linear property
   • EP induced frequency shift
3. Nonlinear dynamics
   • two mechanisms of fast chirping
   • EP transport characteristics

* see Tao Wang et al. Nucl. Fusion 60, 126032 (2020)
Hybrid MHD-kinetic Model *

- Bulk plasma: single-fluid reduced MHD

\[
\frac{\partial \psi}{\partial t} = \frac{R^2}{R_0^2} \nabla \psi \times \nabla \zeta \cdot U + \frac{B_0}{R_0} \frac{\partial U}{\partial Z} + \eta \frac{c^2}{4\pi} \Delta^* \psi
\]

\[
\hat{\rho}_m \left( \frac{D}{Dt} + \frac{2}{R_0} \frac{\partial U}{\partial Z} \right) \nabla^2 U + \nabla \hat{\rho}_m \cdot \left( \frac{D}{Dt} + \frac{1}{R_0} \frac{\partial U}{\partial Z} \right) \nabla U
\]

\[
= \frac{1}{4\pi} \mathbf{B} \cdot \nabla \Delta^* \psi + \frac{1}{R_0} \nabla \cdot [R^2 \nabla \cdot \mathbf{H} \times \nabla \zeta]
\]

\[
\mathbf{B} = R_0 B_0 \nabla \zeta + R_0 \nabla \psi \times \nabla \zeta
\]

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{R^2}{R_0^2} \nabla U \times \nabla \zeta \cdot \nabla
\]

- EPs: pressure tensor term calculated kinetically

\[
\Pi_H(r) = \int dv f_H(r, \mu, v||)[\mu B I + \mathbb{b}(m_H v^2 - \mu B)]
\]

\[
\frac{dr}{dt} = v|| b + \frac{1}{m_H \Omega} b \times [e_H \nabla \phi - v|| \nabla A||
\]

\[
+ (\Omega_H \mu + m_H v^2 + v|| A||) \nabla \ln B]
\]

\[
m_H \frac{dv||}{dt} = b \cdot \left[ \frac{e_H}{\Omega_H} \left( v|| + \frac{A||}{m_H} \right) \nabla \phi + \frac{\mu}{m_H} \nabla A|| \right] \times \nabla \ln B
\]

\[
+ \frac{e_H}{m_H \Omega} b \cdot \nabla A|| \times \nabla \phi - \mu \Omega_H b \cdot \nabla \ln B
\]

\[
\frac{d\mu}{dt} = 0, \quad \phi = -\frac{UB_0}{c}, \quad A|| = \frac{e_H R_0}{c R} \psi
\]

• $R_0 = 1.65 \, m$, $a = 0.40 \, m$
circular cross section,
• $n_{i0} = 2.0 \times 10^{19} \, m^{-3}$,
• $B_0 = 1.3 \, T$, weakly RS equilibria, $q_0 \sim 2$, $q_a \sim 4$,
• $n = 3$ only

$q_{\min} = 1.94 \rightarrow 1.86$: $n = 3$ RSAE FS

$\omega_{\text{RSAE}} \sim \omega_{\text{TAE}}/2 \rightarrow \omega_{\text{TAE}}$
• $R_0 = 1.65\ m$, $a = 0.40\ m$
circular cross section,
• $n_{i0} = 2.0 \times 10^{19}\ m^{-3}$,
• $B_0 = 1.3\ T$, weakly RS equilibria, $q_0 \sim 2$, $q_a \sim 4$,
• $n = 3$ only
• co-inject P-NB, $E_b = 45\ keV$
• anisotropic slowing-down
• strong drive: $n_{H0}/n_{i0} = 5\%$

open question: how does the EP DF evolve in long timescale?
Overview: EP-induced linear frequency shift

Taking the case with $q_{\text{min}} = 1.90$ as a reference:

- Clear differences also in mode structures:
  - the non-perturbative effect of EPs.
Linear resonance analysis: which particles are resonant?

$\Omega$ Effective power transfer

$\omega_\text{res}(r_{eq}, E) \times \omega_A^{-1}$

$\frac{E}{E_b}$

$q_{\text{min}} = 1.90$ reference case: broad resonance region in phase space.

Effective power transfer $\sim$ DF gradient * res. denominator * mode amplitude.
EP-shifted frequency to maximize power transfer

- Comparing normalized power transfer in phase space.
- EP-shifted frequency is weighted by all resonant areas.

$q_{\text{min}} = 1.94$
upward frequency shift

$q_{\text{min}} = 1.86$
downward frequency shift
- EP-shifted mode (excited state) relax back to eigenstate.
- The chirping rate is non-adiabatic: comparable with w-p trapping rate.
EP transport expected to be nonlocal

- $\omega_{\text{res}} = n\bar{\omega}_d + (n\bar{q} - m + \ell)\omega_t$
- $\bar{\omega}_d$: precessional frequency
  (low for well circulating EPs)
- $\omega_t$: poloidal transit frequency

- Vanishing shear near $q_{\text{min}}$
  small radial variation of $\omega_{\text{res}}(r)$.

- Mode saturate when EPs nonlocally “experience” spatially non-uniform mode structure.
Global-scale EP transport

- Saturation when EP decouples with the mode.
- Negligible direct EP loss: radially localized mode
More on fast frequency chirping (convection mechanism)

- High frequency ($q_{\text{min}} = 1.86$) case with EPM character in linear stage.
- A downward chirping “convective” branch dominates in early NL stage.
More on fast frequency chirping (convection mechanism)

- Convective amplification by phase locking (also non-adiabatic chirping).
- Quickly dissipated by continuum damping.
Observation: **enhanced amplitude after saturation**

- Non-adiabatic chirping extends phase space resonant region.
Summarizing: RSAE-EP dynamics

• Fast (non-adiabatic) chirping is induced by EP non-perturbative effect:
  o they are in fact, intrinsically connected,
  o may explain a number of observations.

• Two mechanisms of non-adiabatic chirping: AE-origin relaxation and EPM-like convection.
  o Relaxation branch dominates in RS equilibrium.

• EP transport is convective and usually global (for low-n).
Experimental validation?

RSAE bursts and bifurcating fast chirping in HL-2A*

* Shi et al. Nucl. Fusion 60, 064001 (2020)