Nonlinear gyrokinetic particle simulation of the beta-induced Alfvén eigenmode

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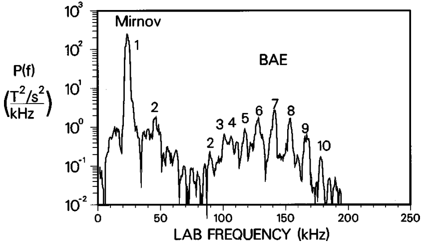
Background

Beta-induced Alfven eigenmode (BAE) is a low frequency mode with $k_{\|} = 0$, which is due to the plasma finite pressure effect under the geodesic curvature. It is widely observed in tokamak experiments and is a major concern because it can be easily destabilized by the energetic particles.

BAE dispersion relation:

$$\omega_{BAE} = \sqrt{7/4 + \tau}\frac{v_i}{R} + O(\epsilon) \quad (1)$$

Here $\tau = T_e/T_i$, v_i and R are ion thermal velocity and major radius, respectively. $O(\epsilon)$ means high order term.



An example of a "BAE cluster" in experiment. (from Heidbrink 1999 Phys. Plasmas vol.6, 1147.)

GTC simulation of the BAE linear excitation:

H. S. Zhang et al, *Phy. Plasmas* **17** 112505 (2010).

Outline

- Nonlinear BAE simulation results
- Coherent phase space structures of energetic particles
- Summary

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Nonlinear BAE simulation results

Coherent phase space structures of energetic particles

Summary

Simulation parameters

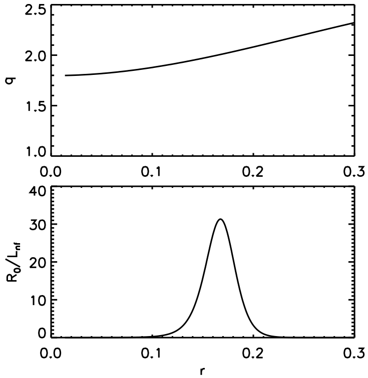
Nonlinear simulation parameters:

Thermal ions:
$\beta = 0.0072$, $T_e = 0$ and
$k_\theta \rho_i = 0.08$.

Energetic particles:
$T_f = 25T_i$, $n_f = 0.01n_i$.

$a/R_0 = 0.33$, $q(r/a = 0.16) = 2$.
$R_0/L_{nf} = 31.0$

Only keep the $(n = 3, m = 6)$ and
$m \pm 1$ harmonics.
Only keep the kinetic nonlinearity.



q profile and energetic particle density gradient profile in radial direction.

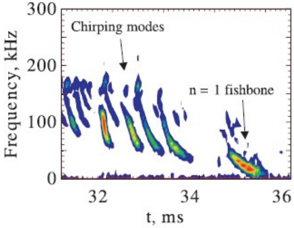
Nonlinear oscillations and frequency chirping/sweeping

$(\omega,\gamma)=(0.96,0.11)\omega_{BAE}$

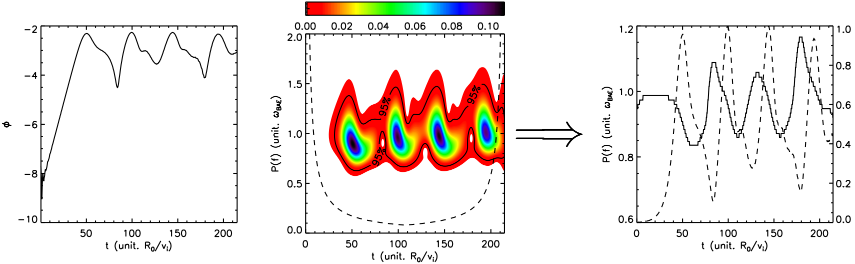
$\omega_{osc}^2 \approx 0.009\omega_{BAE}^2.$

$d\omega_{chirp}/dt \approx 0.007\omega_{BAE}^2.$

Rapid frequency chirping:
Particles probably can not bounce inside the resonant island in the phase space.

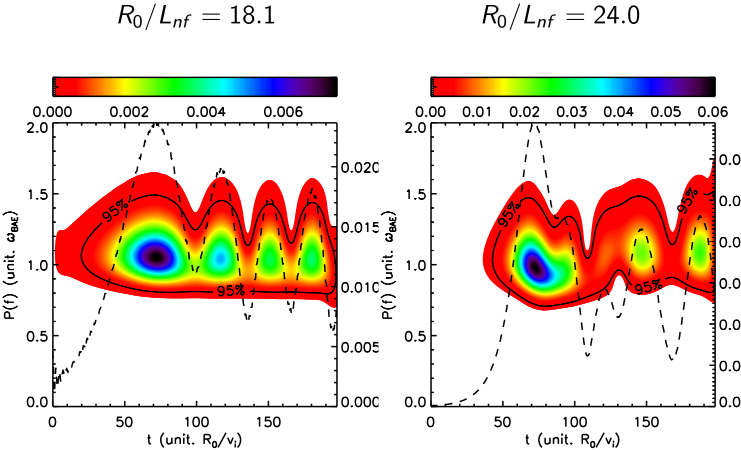


MAST experiment results by Gryaznevich et al, PPCF **46** (2004) S15.



Nonlinear simulation of the ($n = 3$, $m = 6$) BAE mode. (a): Time evolution of the mode amplitude and BAE frequency spectrum. (b): Time evolution of the BAE frequency spectrum. (c): Time evolution of the maximum BAE frequency (solid) and compare with the mode amplitude (dash).

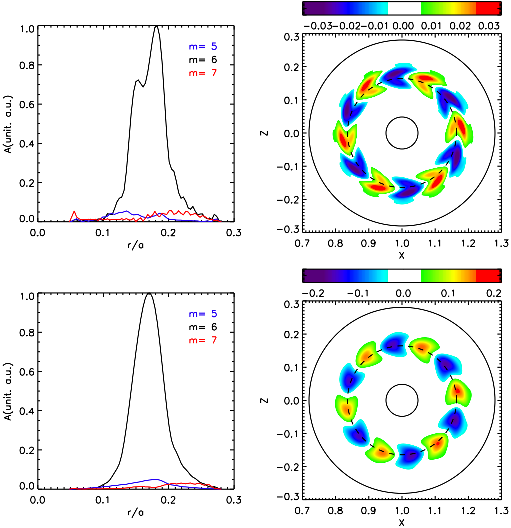
Frequency chirping/sweeping appears with strong drive


$R_0/L_{nf} = 18.1$

$R_0/L_{nf} = 24.0$

BAE amplitude and frequency evolution for different energetic particle density gradient. The density gradients are: $R_0/L_{nf} = 18.1$ and $R_0/L_{nf} = 24.0$, respectively. The excited BAE frequency and growth rate are:$(\omega, \gamma) = (1.03, 0.034)\omega_{BAE}$, $(1.01, 0.068)\omega_{BAE}$ and $(0.96, 0.11)\omega_{BAE}$, respectively.

Nonlinear BAE mode structure



The radial poloidal mode structures. The upper panels and lower panels are snapshots at $t = 85R_0/v_i$ (valley) and $t = 99R_0/v_i$ (peak), respectively.

The nonlinear mode structure is similar with that at the linear stage. The mode is localized at the $q = 2$ surface.

Similar triangle structures are also found in RSAE in both simulation and experiments.

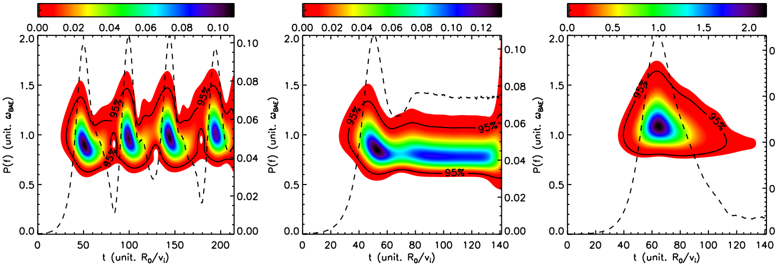
Non-perturbative contribution of the energetic particles.

Role of thermal ion nonlinearity and energetic particle nonlinearity in BAE saturation

Different saturation amplitude:

Thermal ion nonlinearity dominates the initial BAE saturation level.

Both thermal ion and energetic particle nonlinearities are important to the frequency chirping/sweeping and nonlinear oscillations.



BAE simulation with all the kinetic nonlinearity, only thermal ion nonlinearity and only energetic particle nonlinearity, respectively.

Outline

Nonlinear BAE simulation results

Coherent phase space structures of energetic particles

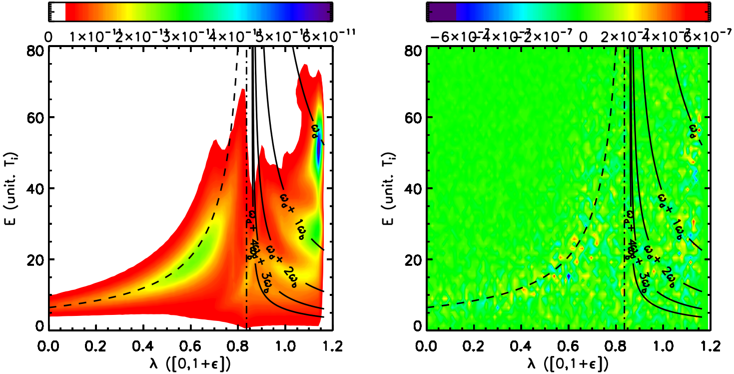
Summary

Linear δf_h^2 and δf_h sturcture in $E-\lambda(\mu/E)$ phase space

Resonance conditions:

$\omega - k_{\|} v_{\|} - p\omega_t = 0$ (passing particles).

$\omega - \omega_d - p\omega_b = 0$ (trapped particles).



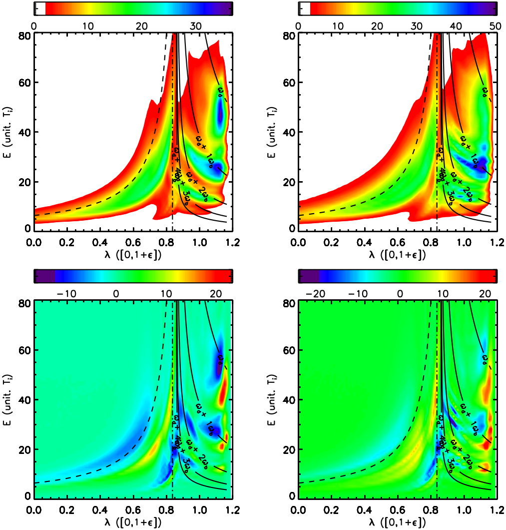
Linear δf_h and δf_h^2 structures in $E-\lambda$ phase space. Particles belongs to the region of $r \in [0.157, 0.175]$ are taken into account.

δf_h^2: $\omega_{BAE} = \omega_d$ resonance dominates.

δf_h: no structures at the linear stage.

Resonant particles: deeply trapped particles and barely passing particles.

Nonlinear δf_h^2 and δf_h sturcture in $E - \lambda$ phase space



Linear and nonlinear δf_h^2 structure in $E - \lambda$ phase space. The nonlinear contour plots are taken at $t = 85 R_0 / V_i$ and $t = 141 R_0 / v_i$, respectively.

δf_h^2 structure:

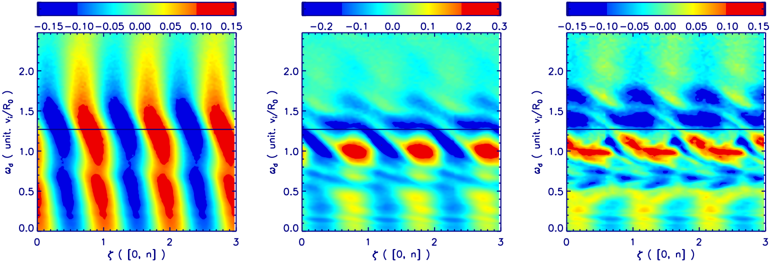
Islands downshift slightly. $\omega_{BAE} = \omega_d + \omega_b$ resonance becomes dominant. Sub-islands appear because of frequency spectrum broadening.

δf_h structure:

Positive islands: gain energy. Negative islands: lose energy. Complex structure appears around the trapped-passing boundary.

Trapped particle $\delta f_h/f_{h0}$ structure in $\omega_d - \zeta$ phase space

Phase space structure for single resonance: precessional resonance.
2D $\omega_d - \zeta(\zeta = \zeta_0 - \omega t/n)$ phase space structure dominates at the linear stage and the beginning of the nonlinear stage.



Linear (a) and nonlinear ((b) and (c)) $\delta f_h/f_{h0}$ structure in $\zeta - \omega_d$ phase space. The solid line is the frequency $\omega_d = \omega_{BAE}$. (b) and (c) are the phase space structures at $t = 70R_0/v_i$ and $t = 122R_0/v_i$, respectively.

Islands form near $\omega_d = \omega_{BAE}$ and move slowly at the nonlinear stage.

No steady rotational structures are found at the nonlinear stage.
$\Longrightarrow$ No nonlinear wave-particle trapping.
Possible reason: dominant resonance condition changes:
Precessional resonance $\Longrightarrow$ bounce-processional resonance.

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Nonlinear BAE simulation are performed by gyrokinetic toroidal code (GTC).

- Nonlinear oscillations along with frequency chirping are observed.
- Nonlinear BAE saturates due to wave-particle interaction with both thermal and energetic particles.
- Both passing and trapped particles contribute to BAE excitation through transit and bounce-precessional resonance, respectively.
- Nonlinear evolution of coherent structures in the energetic particle $\omega_d - \zeta$ phase space are presented and no wave-particle trapping are found in phase space.

Simulation with both wave-particle and wave-wave nonlinearity and the energetic particle transport will be reported later.