

Effects of Zonal Fields on Energetic-Particle Excitations of Reversed-Shear Alfvén Eigenmodes

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ABSTRACT

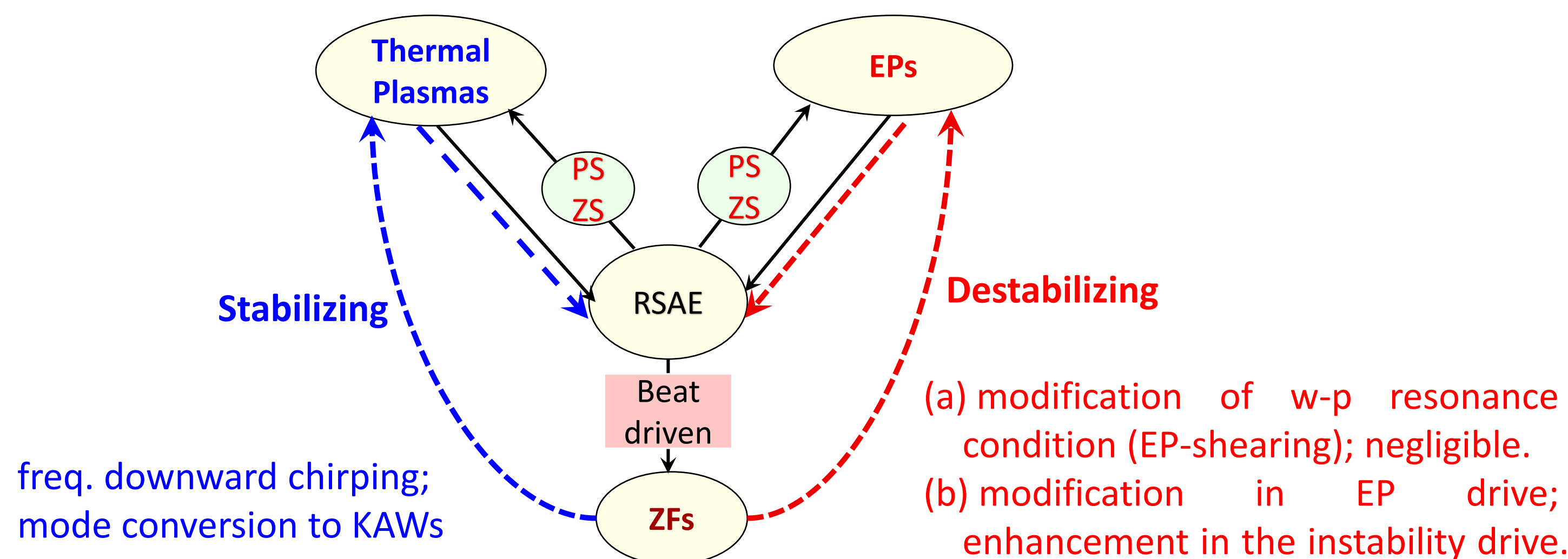
- ZFs, contrary to conventional expectations of ZF stabilization, enhance the EP drive by modifying the EP phase-space zonal structure (PSZS), leading to higher saturation levels.
- ZFs suppress RSAEs by inducing a net downward frequency shift—dominated by zonal current—which enhances coupling to kinetic Alfvén waves (KAWs). This coupling triggers outward KAW propagation and convective (radiative) damping, ultimately saturating the mode.

BACKGROUND

Simulations show that ZFs can be excited by RSAEs through beat-driven mechanism, significantly reducing saturation level [1,2]. Two primary routes have been proposed [3]:

- thermal plasma nonlinearities: frequency shifts or profile modifications (local current and safety factor); enhancing continuum damping;
- EP nonlinearities: modulation of EP-PSZS, altering their resonant interaction with RSAEs.

The underlying physics remains unclear. This work systematically investigates how ZFs affect the RSAE saturation through both routes.



GTC SETTING AND SIMULATION MODEL

EQUILIBRIUM

DIID-D shot #159243 at 805 ms [4].

RSAE are observed in experiments and validated in simulations.

MODELS

EP and thermal ions are described by gyrokinetic model [5] and electrons are described by drift kinetic model.

Using the parallel velocity description, the perturbed gyrokinetic Vlasov equation [6]:

$$(\mathcal{L}_0 + \delta\mathcal{L})\delta F = -\delta\mathcal{L}F_0, \quad (1)$$

$$\mathcal{L}_0 = \frac{\partial}{\partial t} + (v_{\parallel} \mathbf{b}_0 + \mathbf{v}_d) \cdot \frac{\partial}{\partial \mathbf{X}} - \frac{\mu \mathbf{B}_0^*}{B_0} \cdot \nabla B_0 \frac{\partial}{\partial v_{\parallel}}, \quad (2)$$

$$\delta\mathcal{L} = \left(\mathbf{v}_E + \frac{v_{\parallel} \delta \mathbf{B}_{\perp}}{B_0} \right) \cdot \frac{\partial}{\partial \mathbf{X}} - \left(\frac{\mu \delta \mathbf{B}_{\perp} \cdot \nabla B_0}{B_0} + Z \frac{\mathbf{B}_0^*}{m B_0} \cdot \nabla \delta \phi + \frac{Z}{cm} \frac{\partial \delta A_{\parallel}}{\partial t} \right) \frac{\partial}{\partial v_{\parallel}}, \quad (3)$$

For a single n mode simulation with zonal components, Eq. (1) $\Rightarrow$

$$(\mathcal{L}_0 + \delta\mathcal{L}_n + \delta\mathcal{L}_z)(\delta F_n + \delta F_z) = -(\delta\mathcal{L}_n + \delta\mathcal{L}_z)F_0, \quad (4)$$

$\mathcal{L}_n$ and $\mathcal{L}_z$: the perturbed propagators with the toroidal mode number n and zonal components of the electromagnetic fields.

ZF EFFECTS ON RSAE VIA EP DYNAMICS

Three cases are carried out for the most unstable $n = 4$ RSAE:

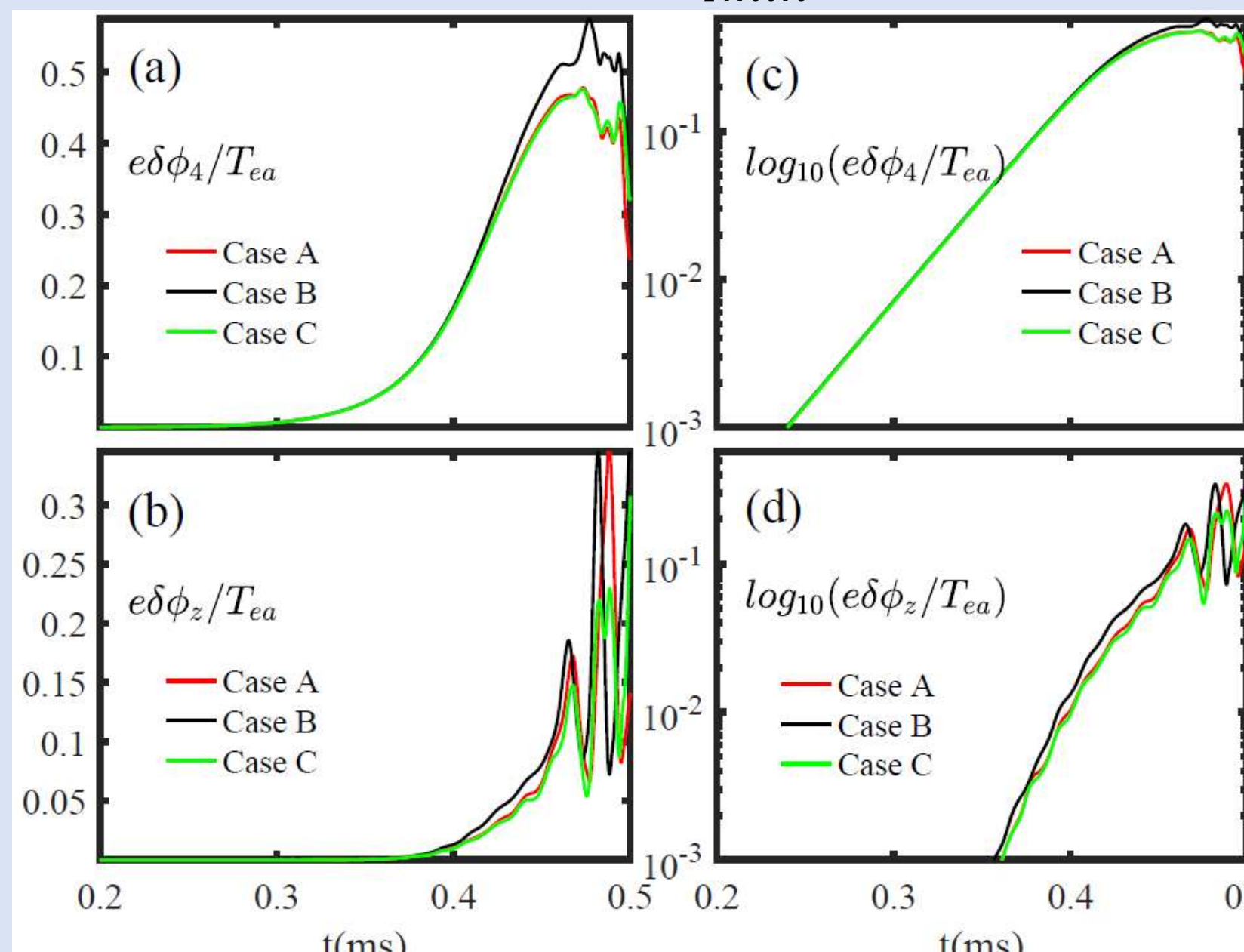
Case A: the No-ZFs case; $\delta\mathcal{L}_z = 0$ to remove the effects of ZFs on EP.

Case B: the Full-ZFs case; $\delta\mathcal{L}_z \neq 0$ on both sides of Eq. (4) is kept for EP.

Case C: the Partial-ZFs case; $\delta\mathcal{L}_z \neq 0$ in the RHS but $\delta\mathcal{L}_z = 0$ in the LHS, to remove the so-called shearing effects due to ZFs.

SIMULATION AND THEORETICAL RESULTS

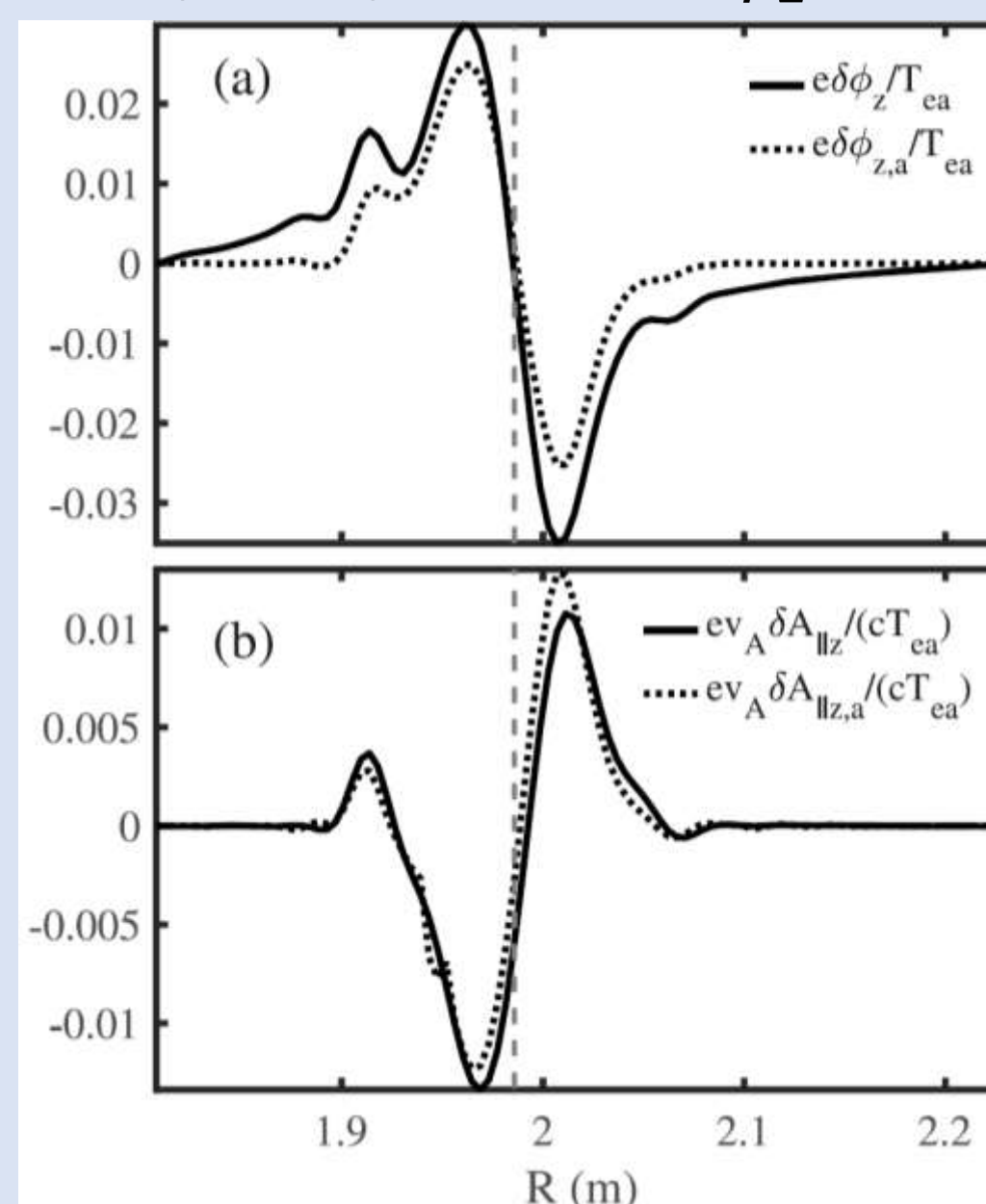
Time history of $e\delta\phi_4/T_{ea}$ (a), $e\delta\phi_z/T_{ea}$ (b), and the corresponding plots using a base-10 logarithmic scale (c) and (d), normalized by the on-axis electron temperature T_{ea} , for the selected $n = 4$ modes on q_{min} flux surface from Case A (red), B (black) and C (green).



- The Full-ZFs Case B exhibits a higher initial saturation level than the No-ZFs Case A and Partial-ZFs Case C.
- The No-ZFs Case A overlaps with the Partial-ZFs Case C; EP zonal shearing effects in EPs are negligible (weak stabilization).

Results can be understood analytically in terms of **the general fishbone-like dispersion relation** [7] with the correspondingly different **EP phase-space zonal structures** induced by the ZFs [8,9].

Radial profiles of (a) $\delta\phi_z$ and (b) $\delta A_{\parallel z}$ from the Full-ZFs Case B (solid line) and the analytically derived $\delta\phi_z$ and $\delta A_{\parallel z}$ using Eqs. (5) and (6) (dot dash line) at $t=0.42$ ms.

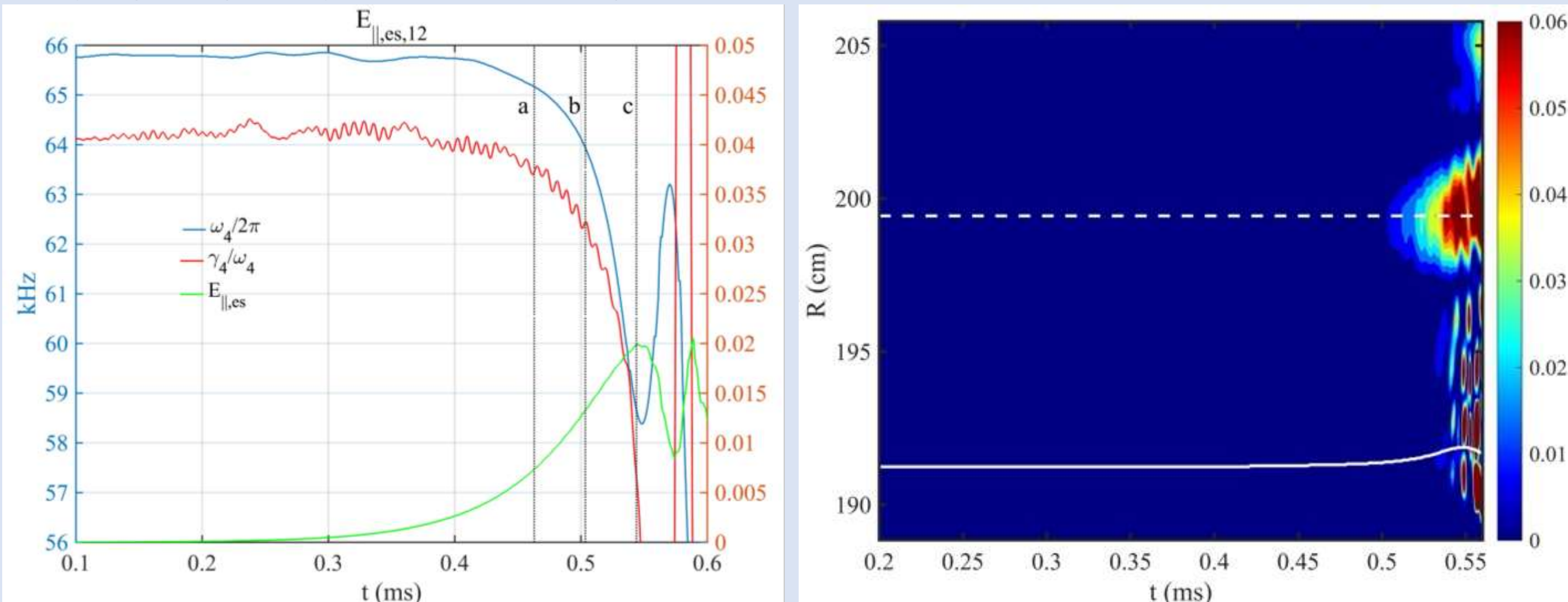


- The analytical expressions of $\delta\phi_z$ and $\delta A_{\parallel z}$ generated by beat-driven RSAE are derived by considering a large aspect-ratio tokamak with circular magnetic surfaces [3]:
- $\frac{A_z}{c} \simeq \frac{c}{B_0} \omega_{0r}^2 \frac{\partial}{\partial r} [k_{\theta 0} k_{\parallel 0} |\delta\phi_0|^2]$ (5)
- $\Phi_z \simeq \frac{c}{B_0} \frac{1}{\omega_{0r}^2} (1 + c_0 \eta_i) \partial_r [k_{\theta 0} \omega_{*in} |\delta\phi_0|^2]$ (6)
- The analytical and simulation results are in good agreement for both ZFs.

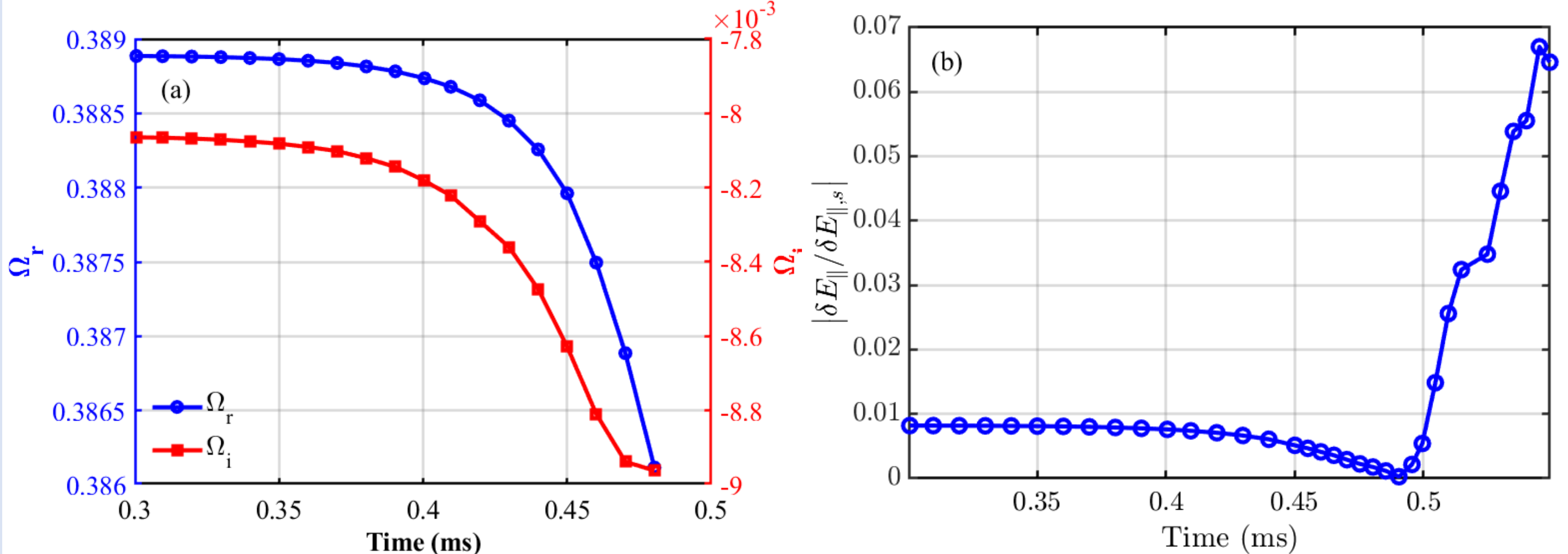
ZF EFFECTS ON RSAE VIA THERMAL PLASMA DYNAMICS

EPs are treated linearly; thermal plasmas are full nonlinear.

(Left) Time evolution of **RSAE frequency (blue)**, **normalized growth rate (red)**, and **amplitude of the parallel electrostatic field (green)**. (Right) Corresponding time-resolved radial profile of the parallel electric field.



A theoretical eigenmode equation by incorporating FLR effects and electron Landau damping dynamics in nonuniform plasmas is developed and numerically solved.



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