Nonlinear Particle Simulation of Radio Frequency Waves in Tokamak

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Abstract. An electromagnetic particle simulation model has been formulated and verified for nonlinear processes of radio frequency (RF) waves in fusion plasmas [1]. The simulation model has been implemented in the gyrokinetic toroidal code (GTC) [2]. Nonlinear particle simulations of RF waves in tokamak have been carried out for the first time with a real electron-to-ion mass ratio by using the GTC code. The upshift and broadening of the poloidal spectrum of the wave-packets due to the toroidicity and wave diffraction are verified in the simulation of the lower hybrid (LH) wave propagation in tokamake geometry [3]. Nonlinear simulations of LH waves demonstrate that current can be driven by LH waves, that LH wave amplitude is locally enhanced due to the particle trapping, and that LH pump wave can decay into an ion plasma wave and a LH sideband wave [4]. In the nonlinear simulation of ion Bernstein wave (IBW) in a tokamak, parametric decay instability (PDI) is observed where a large amplitude pump wave decays into an IBW sideband and an ion cyclotron quasi-mode (ICQM). The ICQM induces an ion perpendicular heating, with a heating rate proportional to the pump wave intensity [5].

1. Introduction

Radio frequency (RF) waves are the most efficient tools for steady state operation of tokamak, which are widely used to heat plasma, control current profile and suppress magneto-hydrodynamics instabilities. The nonlinear effects of RF waves become more important in tokamak plasmas with the availability of high heating power. For example, nonlinear parametric decay instability of RF waves has been observed in many experiments [7, 8]. Traditional simulation methods (WKB and full wave) can not address nonlinear physics. In this work, we develop global particle simulation approach to study nonlinear physics of RF waves (nonlinear wave-particle interaction, ponderomotive effects, parametric decay instabilities etc.)

A fully nonlinear electromagnetic particle simulation model for RF waves in the toroidal geometry has been successfully implemented in the gyrokinetic toroidal code (GTC) [1]. In this electromagnetic simulation model, the ion dynamics is described by 6D Vlasov equation and the electron dynamics is described by 5D drift kinetic equation. The ion cyclotron orbit is integrated by Boris method, which has the advantage of energy conservation with long simulation time duration [5, 6]. Both linear and nonlinear simulations of LH waves and IB waves by using GTC code will be reported here.

2. Electromagnetic simulation of linear mode conversion of lower hybrid waves

Linear simulation of the lower hybrid (LH) wave-packet in the tokamak shows that the wave propagates faster in the high field side than the low field side, in agreement with a ray tracing calculation as shown by Fig. 1 [9]. Global electromagnetic simulation confirms that the toroidicity induces an upshift of parallel refractive index when LH waves propagate from the tokamak edge toward the core, which modifies the radial position for the mode conversion between slow and fast LH waves as shown by Fig. 2 [3]. Furthermore, moving LH antenna launch position from low field side toward high field side leads to larger upshift of the parallel refractive index, which helps the slow LH wave penetration into the tokamak core. The broadening of the poloidal spectrum of the wave-packet due to wave diffraction is also verified in the simulation. Both the upshift and broadening effects of the parallel spectrum of the wavepacket modify the parallel phase velocity and thus the linear absorption of LH waves by electrons Landau resonance as shown by Fig. 3 [3].

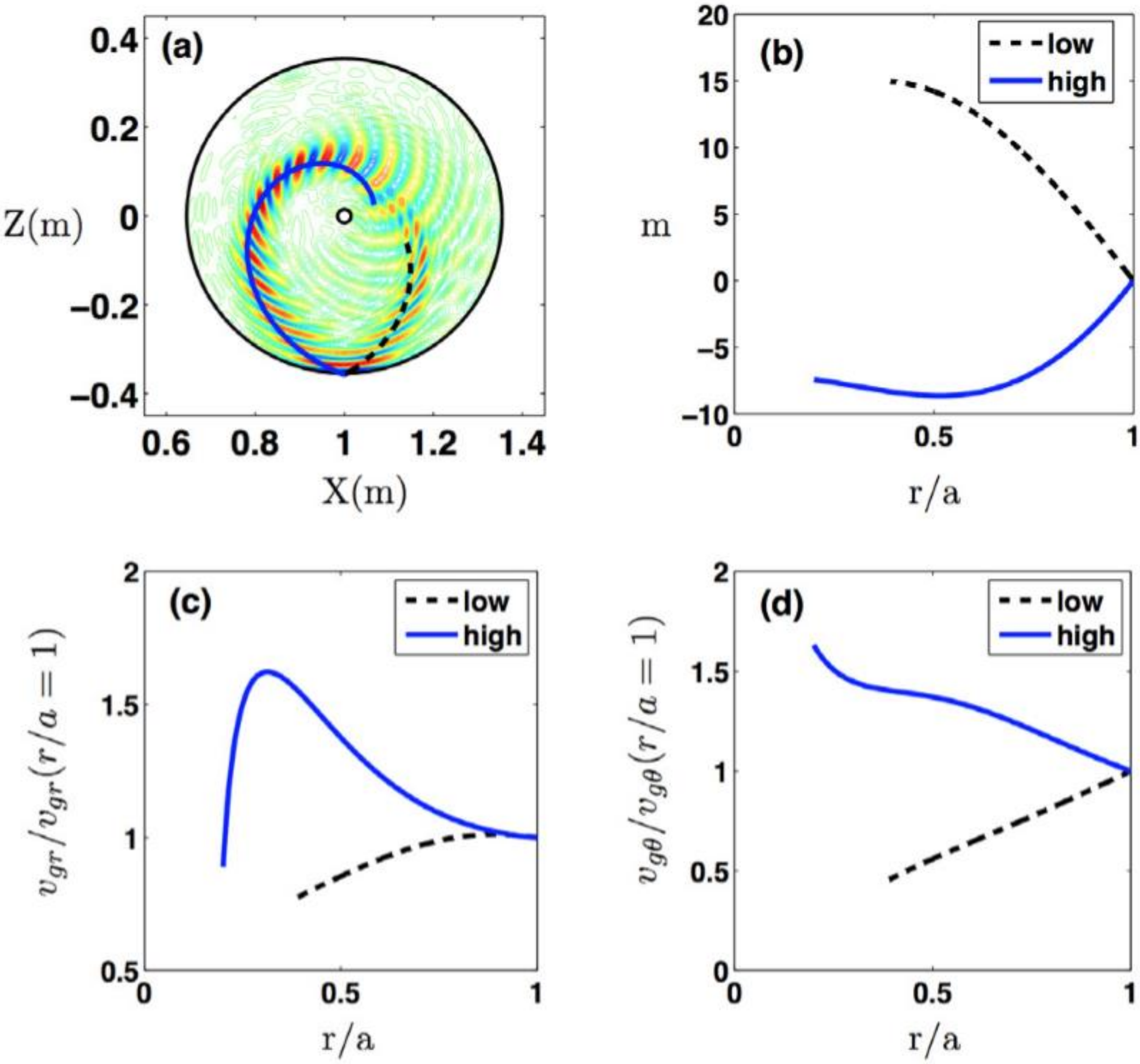

FIG. 1. (a) WKB simulation of the ray trajectories is compared to GTC simulation in the toroidal geometry. (b)–(d) are the evolutions of the m number, radial group velocity and the poloidal group velocity of the ray, respectively. The blue solid line represents the ray in the high field side, and the black dashed line represents the ray in the low field side.

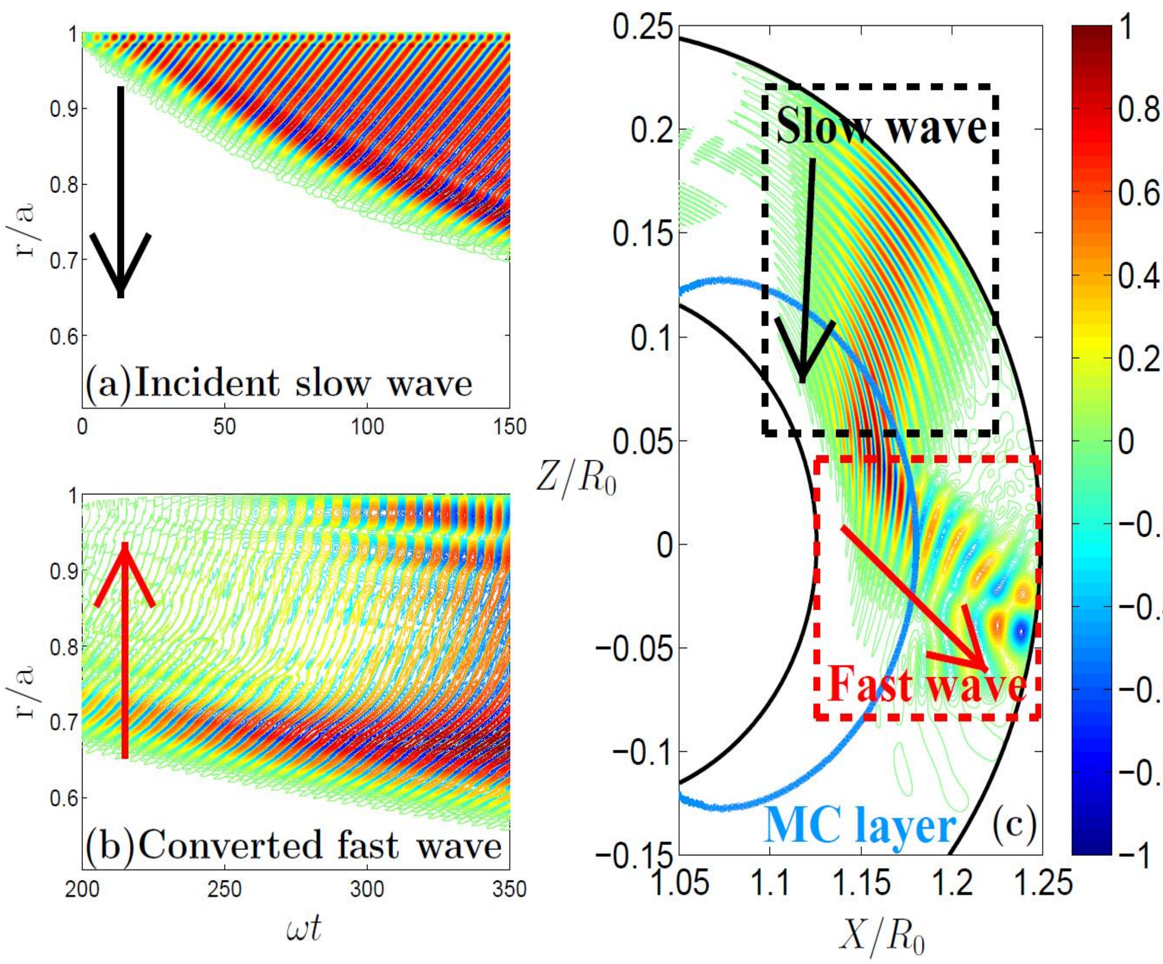

FIG. 2. The 2-D radial-time plot of (a) the incident slow LH wave and (b) the mode converted fast LH wave. Panel (c) shows the mode structures of the slow and fast LH waves in poloidal section. The arrows show the wave propagation directions. The blue line in (c) is the analytic calculation of the mode conversion layer assuming poloidal harmonic m=0.

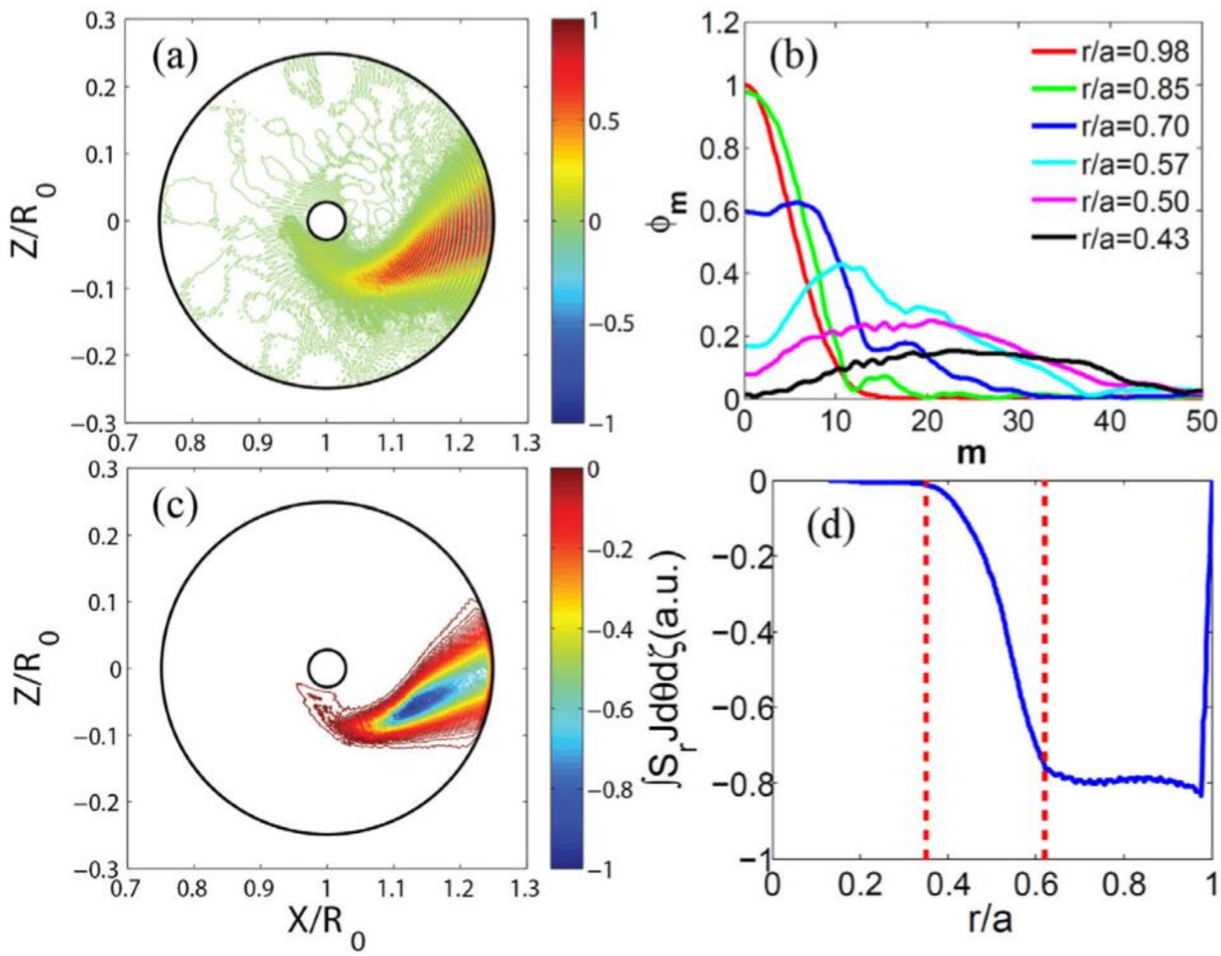

FIG. 3. (a) A single pass of slow LH wave propagation in the poloidal cross-section. The color scale represents the electrostatic potential φ in arbitrary units. Panel (b) shows the poloidal spectra of the wave-packets at different flux-surfaces. Panels (c) shows the radial component of the energy flux density Sr in the poloidal cross-section, and the color scale represents Sr in arbitrary units. Panel (d) shows the radial dependence of the energy flux $S(\mathrm{r}) = \int S_r J d\theta d\zeta$ *, and we can see that the absolute value of the energy flux decreases in the region between the red dashed lines, which is due to the wave power deposition in the plasma through electron Landau damping.*

3. Electromagnetic simulation of nonlinear physics of lower hybrid waves

The nonlinear particle simulation shows that the LH wave pattern amplitude can be locally enhanced due to the nonlinear electron trapping effect as shown by Fig. 4, which also affects the LH wave pattern structure and propagation. For comparison, the traditional WKB and full wave approaches study the LH wave propagation based on the linear theory, which is not accurate in the presence of the high LH wave power. The parametric decay of the pump LH wave is also observed when the wave amplitude increases, and a sideband wave with the opposite phase velocity and a low frequency ion plasma wave are generated during the PDI (Fig. 5). In the simulation of nonlinear PDI of LH waves, we apply a much higher density value at the plasma edge, which shows the nonlinear simulation capability. Further study of LH wave PDI with realistic experimental parameters will be carried out in the next step.

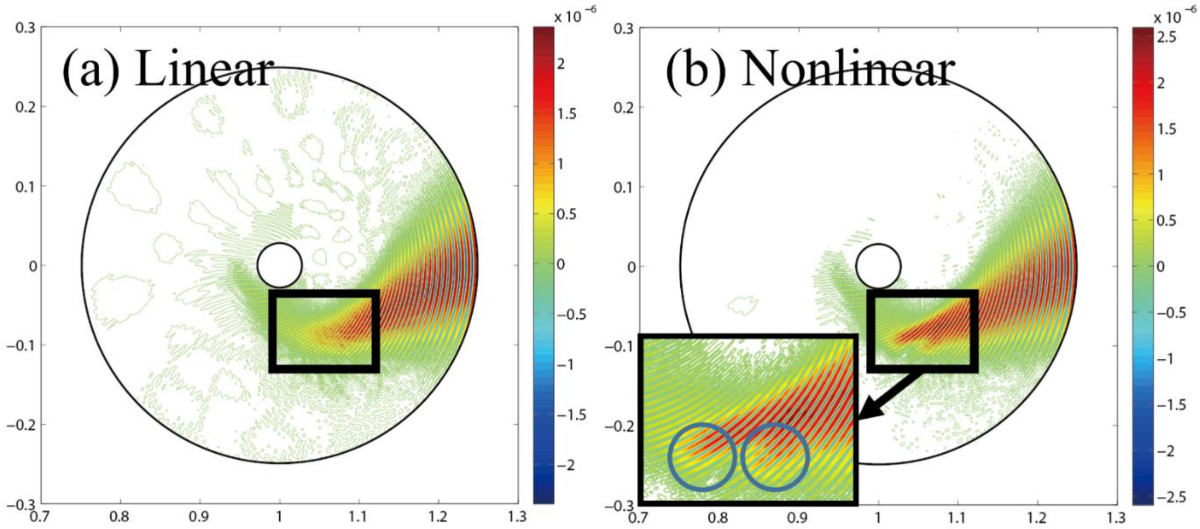

FIG. 4. (a) Linear simulation shows that the LH wav amplitude decreases in the absorption region. (b) Nonlinear simulation shows that the LH wave amplitude is enhanced in the absorption region through electron trapping effect. The superposition of the linear oscillation and nonlinear bounce oscillation of LH waves modifies the wave pattern structures in real space.

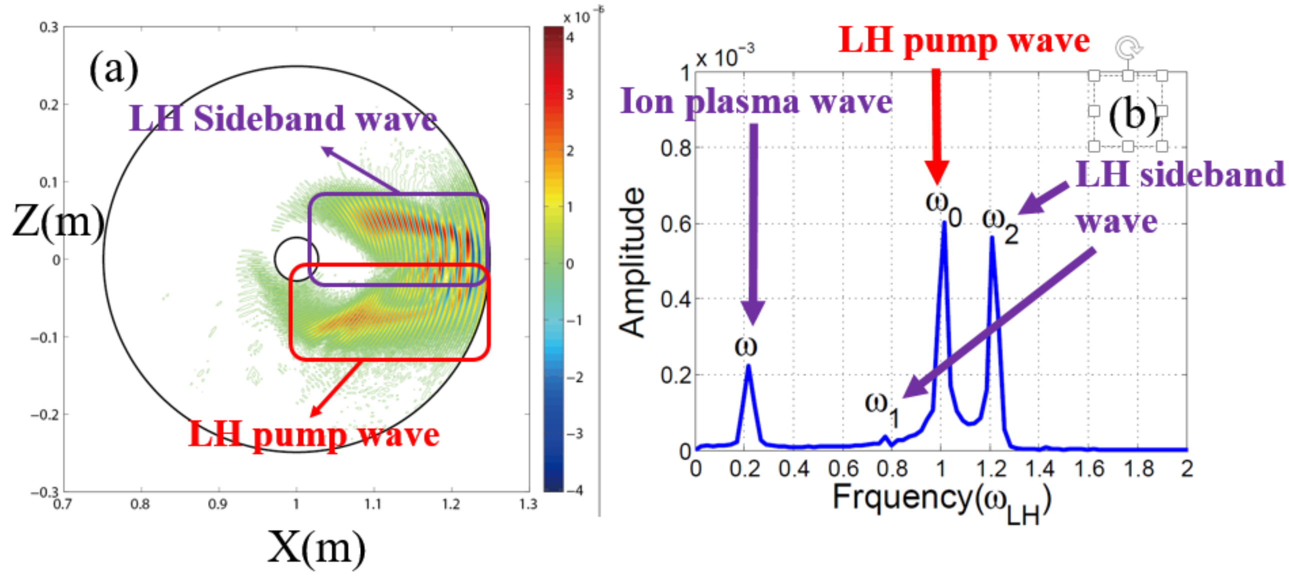

FIG. 5. (a) LH wave pattern structure during PDI. (b) The pumped LH wave can decay into a sideband LH wave and an ion plasma wave. This simulation uses a much higher density value at the plasma edge, which shows the nonlinear simulation capability. Further study of PDI by using realistic experimental profile will be carried out in the next step.

4. Nonlinear parametric decay instability of ion Bernstein waves

In the nonlinear simulation of ion Bernstein wave (IBW) in a tokamak, PDI is observed where a large amplitude pump wave decays into an IBW sideband and an ion cyclotron quasi-mode (ICQM) as shown by Fig. 6. The ICQM induces an ion perpendicular heating, with a heating rate proportional to the pump wave intensity (Fig. 7) [5].

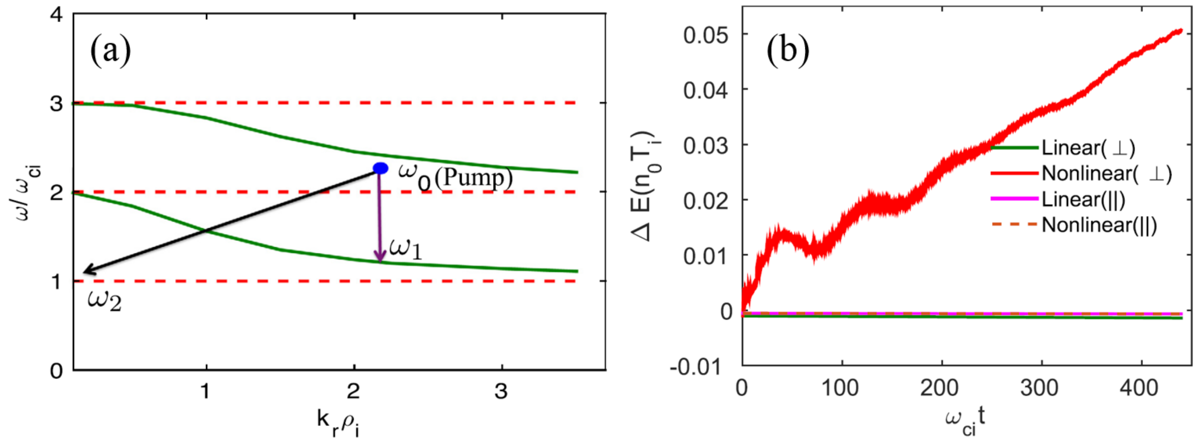

FIG. 6 (a) Schematic of an IBW parametric decay process. Pump wave (ω_0, k_0) *decays into an IBW side band* (ω_1, k_1) *and an ion cyclotron quasi-mode (ICQM)* (ω_2, k_2). *(b) Time history of change of kinetic energy of ion. Green and magenta lines represent the energy change during linear simulation in the perpendicular and parallel directions, respectively. Red and dotted lines indicate the energy change during nonlinear simulation in the perpendicular and parallel direction, respectively.*

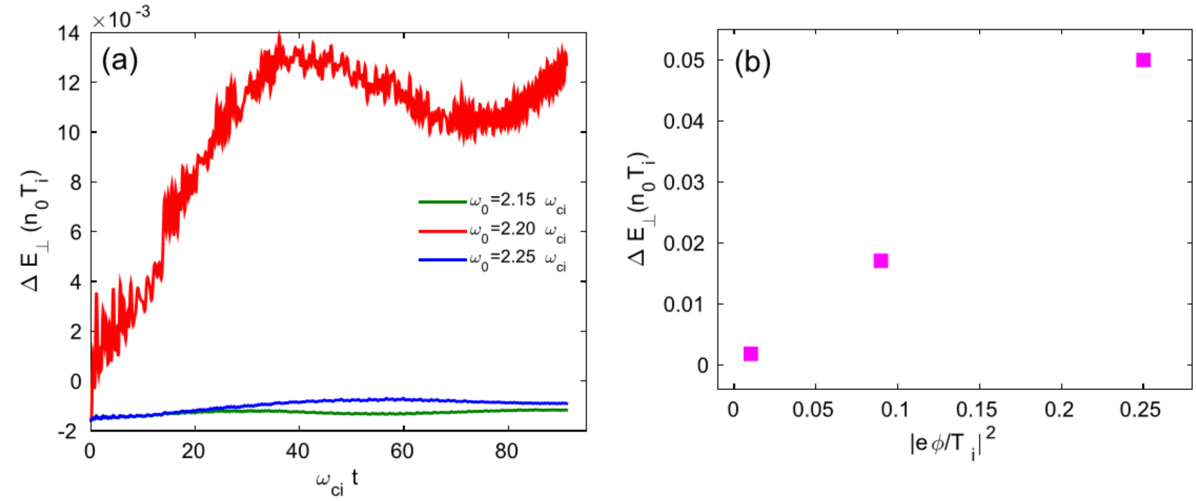

FIG. 7. (a) Time history of change of perpendicular kinetic energy of ion for different pump wave frequency and (b) change in kinetic energy of ion as a function of intensity of the pump wave.

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