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Nonlinear Phase Dynamics in the process of Mode Conversion

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Mode conversion normally occurs in a localized region where the plasma parameters are inhomogeneous[1]. Then two modes with same frequency will coexist there and their wave numbers will also coalesce due to some critical set of parameters[2]. Hence one mode will be strongly coupled or converted to another. Since a wave from the plasma periphery can couple to another wave which is able to be efficiently damped by the thermal motion of electrons and ions, mode conversion acts as a significant mechanism for the radio-frequency (RF) heating of thermonuclear plasmas.

Conventional mode conversion usually involves modes with different wavelengths but same frequencies. One can consider a wavenumber relevant to the spatial coordinate $k(x) = \partial\Theta/\partial x$, where Θ is the phase of the displacement $\xi(x,t)$. And when approaching the critical layer or the spatial singularity point $x = x_c$, $k(x)$ will become divergent and here mode conversion occurs[2]. Due to the spatial singularity, the spectrum in k-space becomes broadened and then excites a converted mode.

Conversion between modes with same frequency implies a linear time-dependent phase, or in other words, there's only linear phase dynamics. Hence it is natural to raise several new questions: what will happen in the process of mode conversion between modes with different frequencies? Should that mean that the effects of nonlinear phase dynamics need to be taken into consideration? To answer such questions, now we choose a frequency related to the time coordinate $\omega(t) = -\partial\Theta/\partial t$ and consider a conversion between different frequencies. Apparently it is anticipated that there might also be a similar but temporal singularity accompanied with a broad spectrum in ω-space.

In the realm of plasma physics, mode conversion between different frequencies is accessible when it comes to the continuous spectrum of Alfvén wave, where the collective surface disturbance converts into local Alfvén oscillations, leading to the phenomenon of a spatial phase mixing which can heat the plasma[3,4].

Here, we propose nonlinear phase dynamics to interpret mode conversion process from a more physical perspective. We also provide numerical solutions to support and verify our theory. It is shown that continuous spectrum is related to the nonlinearity of phase. And when the phase becomes extremely nonlinearized, there will exist a phase finite-time singularity (FTS), as is illustrated in Figure 1(c)(d)(e)(f), accompanied with a highly nonlocalized spectrum in ω-space, which is qualified to accelerate mode conversion between different frequencies.

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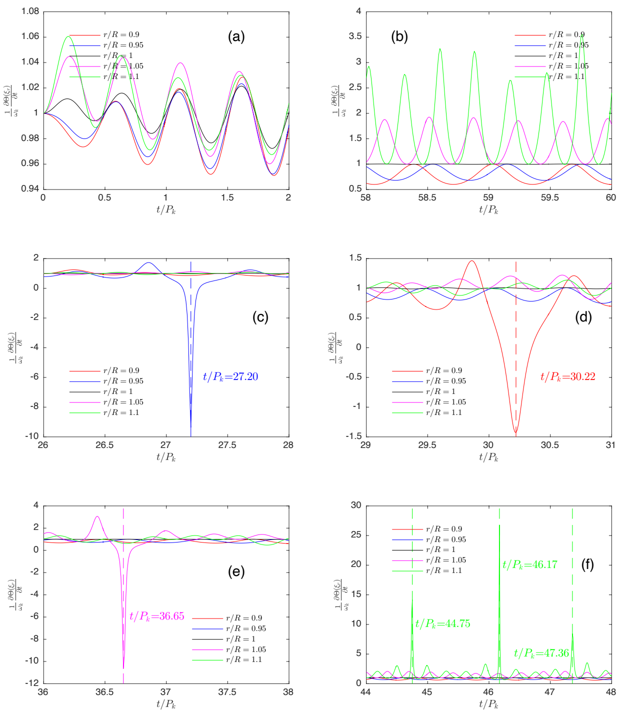

Figure 1. Temporal evolutions of the normalized time derivatives of phases of the radial displacement ξ_r at different places. (a) and (b) show the time slices related to the beginning and the end of the process we investigated. (c)(d)(e)(f) display the slices when the FTS occurs