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Saturation mechanism for energetic particle induced zonal structure

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Energetic particles can excite modes like toroidal Alfven eigenmode (TAE) and energetic particle mode (EPM), which may cause strong energetic particle transport and affect fusion plasma confinement. However, recent experiments show that EPs can improve the plasma confinement in some cases, for example in the cases of the FIRE mode and the F-ATB plasma. These experiments indicate that fast particles and even alpha particles can generate ITB under certain conditions, thereby suppressing the ion scale turbulence and benefitting the total confinement of fusion plasma. Several mechanisms have been proposed to explain this confinement enhancement, such as the fast particle dilution mechanism, electromagnetic stabilization, zonal structure (ZS) generation, and etc. Resolving the conflicts between these experiments and previous theories is a problem well worth investigating. Meanwhile, the possible application of these phenomena in future fusion reactors is unclear and deserves further study. It has been known that TAE can spontaneously generate zonal structure through modulational instability, which requires a threshold of the TAE amplitude. But zonal flow can also be forced driven by TAE, in which case the linear growth rate of ZS is twice of the TAE's growth rate.

In this work, we explore the possibility of suppressing turbulence via ZS that is forced driven by TAE. We study at what level the ZS will saturate, and whether ZS is strong enough to affect the ion scale turbulence. We focus on the forced-driven stage of ZS and study the feedback modulation of ZS on the wave-particle resonance relation. When the amplitude of ZS is strong enough, the phase shift from ZS can modify the wave-particle resonance relation, therefore modifying the drive source of ZS and TAE, which leads to the saturation of ZS and TAE. This mechanism is similar to a mechanism proposed for $E \times B$ staircase formation. The effects of EP-induced ZS on the plasma transport will be preliminarily discussed.

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