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Formation, Propagation and Conversion of Transport Barriers Triggered by Dynamical Critical Gradient in Tokamak Plasmas

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Magnetically confined plasma system is well-known for its multi-confinement states. Typical scenarios include the L-mode (L: low confinement), the H-mode (H: high confinement) and the I-mode (I: improved), et al[1, 2]. An 'order parameter' depicting the confinement state is the transport barrier, measured by the shearing rate of the mean E×B flow. The transport barrier could occur near the core or the edge, dubbed as internal/edge transport barrier (ITB/ETB). It is a key structure for maintaining the high confinement state of magnetically confined plasma systems. Transitions between different type of transport barriers, (typically, the ITB and the ETB), cause the conversions of different confinement states. The synergism between the global dynamics (i.e., propagation) and the local dynamics (i.e., transition) is critical to understanding the transition mechanisms of different confinement states.

Plasma profiles tend to stay near a critical gradient, known as self-organized criticality (SOC), which gives rise to profile stiffness[3]. This stiffness strongly constrains the transition of confinement states, especially in the plasma core region that lacks boundary conditions. To form a transport barrier, the profile stiffness needs to be weakened, breaking the old SOC state and establishing a new one. The experimental evidence suggested that the profile stiffness is correlated with the rotational flow, i.e., by increasing the flow shear, the profile stiffness could be softened[4]. Thus, the critical gradient should dynamically align with the flow evolution rather than being an adjustable parameter.

In this work, we propose a 1D reduced model with a dynamical critical gradient (DCG) to study the formation, propagation, and conversion of the transport barriers. In contrast to the commonly adopted static critical gradient, an evolving critical gradient self-consistently softens the profile stiffness, so as to facilitate the generation of transport barriers. This is especially crucial to the ITB formation. Numerically, we show that the inhomogeneity of turbulent and neoclassical diffusivities can induce the global wave front propagation of the transport barrier. When the heating power ramps quickly, the ITB propagates unidirectionally to the edge region and converts into an ETB. For slow power ramping, the propagating ITB will bifurcate into bidirectional wavefronts and finally convert into a steady DTB (double transport barrier) state. Our model uncovers the vital role of a dynamical 'profile-stiffness' in depicting the global dynamics of the transport barrier.

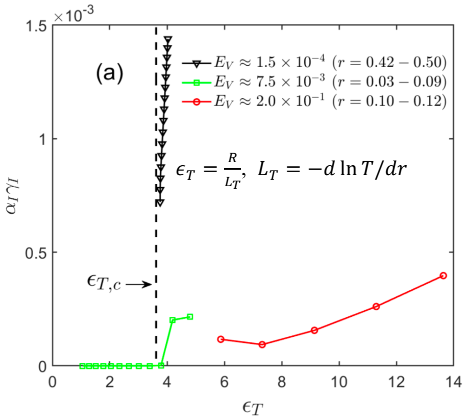

Figure 1. Stiffness with different mean flow shear Ev.

References
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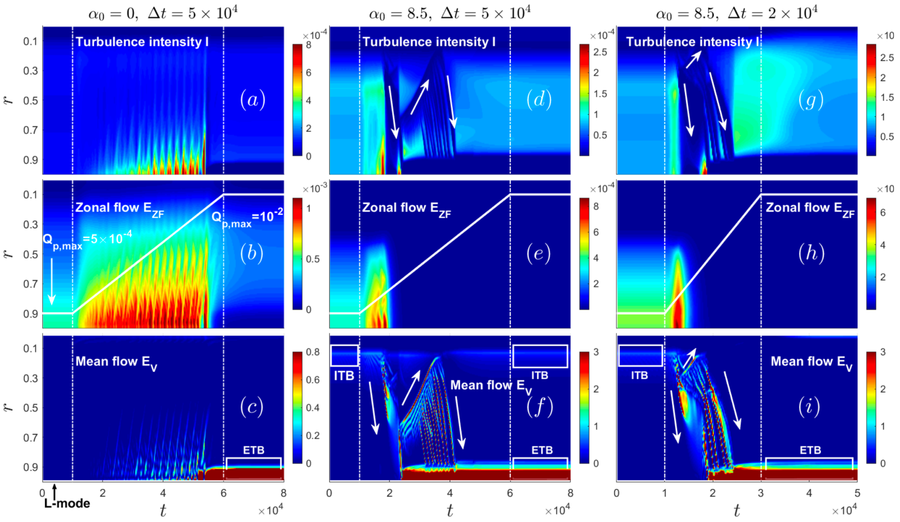

Figure 2. Spatiotemporal evolutions of turbulence, zonal flow, and mean flow in the cases of w/o DCG (a-c) and w/ DCG (d-f) under a slow power ramp, and w/ DCG (g-i) under a quick power ramp. The input power is increased from 5×10^{-4} to 1×10^{-2} with a duration of $\Delta t = 5\times10^4$ for the slow ramp, and $\Delta t = 2\times10^4$ for the quick ramp.