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L-H transition physics and non-perturbative statistical theory

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Magnetically confined plasmas constitute one of the important examples of complex systems operating far from equilibrium [1]. Despite the complexity, self-regulatory behaviour often emerges spontaneously and plays a vital role in plasma confinement. For instance, when the input power exceeds a critical power, the transition from a low-confinement mode (L-mode) to a high-confinement mode (H-mode) can occur spontaneously, where plasmas organise themselves into an 'ordered', high-confinement state. Reproduced in different fusion devices (tokamaks, stellarators, reversed field pinch) since the first discovery in 1980s [2], the Low-to-High confinement (L-H) transition is now believed to be triggered by the spontaneous formation of E × B macro/meso scale shear flows (mean shear/zonal flows) which significantly reduce the transport via turbulence suppression by shear flows. In particular, zonal flows generated from small-scale turbulence in turn regulate turbulence by shearing, leading to self-regulatory oscillations (called dithering).

In this paper, we discuss a non-perturbative statistical method, namely a time-dependent density function (PDF) approach that is potentially useful for analysing time-varying, large, or non-Gaussian fluctuations and bursty events associated with instabilities in the L-H transition and the H-mode. First, we present a stochastic prey-predator L-H transition model model by extending the previous deterministic ODE model [3]. We calculate exact time-dependent Probability Density Functions (PDFs) by numerically solving the Fokker-Planck equations and characterize time-varying statistical properties [4,5].

We demonstrate non-trivial effects of stochastic noise on the L-H transition dynamics such as the oscillation amplitude and the duration of the dithering phase. In particular, PDFs exbibit strong deviations from Gaussian PDF and a significant asymmetry around the peak, with the signature of multimodal structure. The snapshots of joint PDs are shown in Figure 1 where x and y axis represent turbulence and zonal flow. The six panels (1-6) are at times t = 5, 10, 20, 30, 40, 50, respectively, revealing striking feature including strongly Second, we apply a novel information geometric method [6] by using information length and show their utility in forecasting transitions and self-regulation between turbulence and zonal flow. Finally, the implications of stochastic noise in edge localized modes which are quasi-periodic oscillations or bursts appearing in H-mode are discussed, with implications for ELM suppression and/or mitigation.

Overall, our results highlight the limited utility of mean value and variance while indicating the possibility that stochastic noise may be an important factor that should be considered in understanding experimental data.

References

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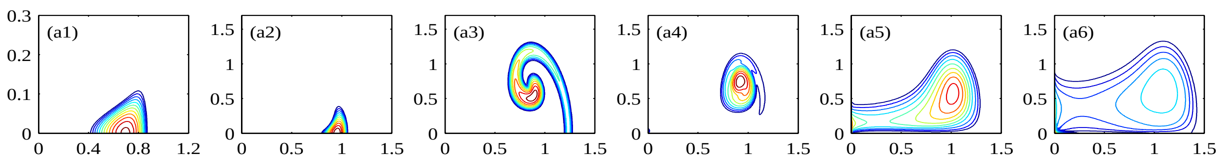

Fig 1: Snapshots of joint PDF of turbulence and zonal flow.