8th Asia-Pacific Conference on Plasma Physics, 3-8 Nov, 2024 at Malacca.

Novel statistical approach to fusion plasma turbulence

Eun-jin Kim[1,2]
[1]Fluid and Complex Systems Research Centre, Coventry University,
[2]Seoul National University
email (speaker): ejk92122@gmail.com

Magnetic confinement plasmas constitute one of the important examples of complex systems operating far from equilibrium. Despite the complexity, self-regulatory behavior often emerges spontaneously and plays a vital role in plasma confinement. To identify and access advanced fusion operational regimes, it is critical to characterize plasma turbulence accurately.

For instance, when an input power exceeds a critical power threshold, the transition from a low-confinement mode (L-mode) to a high-confinement mode (H-mode) occurs spontaneously, where plasmas organize themselves into an ‘ordered’, high-confinement state. Despite over 40 years of research on the L-H transition, its triggering mechanisms and causality relations are not fully understood. Furthermore, turbulence characteristics in the L and H modes are highly variable, often with highly time-varying RMS values of fluctuating electron density and turbulence velocity. On the other hand, the H-mode is subject to quasi-periodic edge-localized modes (ELMs), which can potentially cause significant damage to wall-facing materials. Despite successful ELM suppression and mitigation, e.g., using resonant magnetic perturbations (RMPs), what is necessary for successful control is not fully understood.

To address this, this talk will present novel non-perturbative methods that can capture time-varying, large fluctuations [1-11]. We show strongly non-Gaussian time-dependent probability density functions (PDFs) in fusion plasmas, and how information geometry theory [1-2] helps us understanding self-regulation and causal relations among different variables. In particular, the causal information rate is shown to capture time-varying causal relations much better than the other popular causality analysis such as transfer entropy or information flow [3].

The application will be discussed in the stochastic modeling of the L-H transitions [3-6,9,10], ELMs [7,8] and the two-field fluid drift wave turbulence [11] – the modified Hasegawa-Wakatani (mHW) [11] model Stochastic noises produce random trajectories of turbulence (see Fig. 1), zonal flows, and mean flows, leading to the L-H transition occurring at different times and uncertainty in power threshold while ELM suppression through phase mixing. Power ramping scheduling and different initial conditions also contribute to the uncertainty in the L-H transition power threshold, acting as ``hidden variables”. Furthermore, our careful analysis of mHW model reveals that the classical paradigm of the Reynold-stress-driving of zonal flows can break down far from equilibrium [11].

Overall, our results highlight that often-used plasma parameters given by mean values and a few low-order moments are insufficient to characterize details of plasma turbulence -- plasmas with similar parameters can significantly differ in their statistical properties and evolve into different states over time. The presented methods can also be applied to other systems.

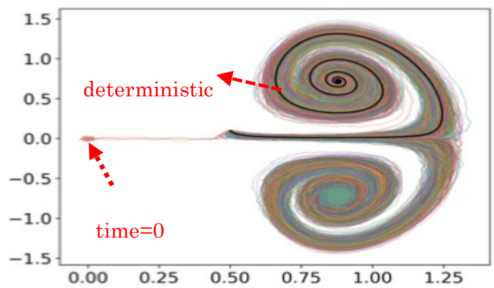

Fig 1. Trajectories diverge over time due to stochastic noise

This work is in part supported by National Research Foundation of Korea (RS-2023-00284119).

References

[1] E Kim, Entropy 23, 1393 (2021)
[2] E Kim, Entropy 23, 1087 (2021)
[3] E Kim & AA Thiruthummal, Entropy 26(17):1-21 (2023).
[4] E Kim and R Hollerbach, Phys. Rev. Res. 2, 023077 (2020).
[5] R Hollerbach, E Kim & L Schmitz, Phys. Plasmas 27, 102301 (2020).
[6] P Fuller, E Kim, B Hnat and R Hollerbach, Phys. Plasmas 30, 102502 (2023)
[7] E Kim and R Hollerbach, Philosophical Transactions of Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 381, 20210226:1-16 (2021)
[8] E Kim and R Hollerbach, Phys. Plasmas 29, 112302:1-24 (2021).
[9] HJ Farre-Kaga, Y Andrew, J Dunsmore, E Kim, TL Rhodes, L Schmitz, and Z Yan, Euro Phys Lett. 142, 64001 (2023).
[10] Y Andrew, J Dunsmore, T Ashton-Key, HJ Farre-Kaga, E Kim, TL Rhodes, L Schmitz, and Z Yan, Plasma Physics and Controlled Fusion, **66** 055009 (2024).
[11] P Fuller et al, in preparation (2024).