9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Global linear drift-wave eigenmode structures on flux surfaces in stellarators: ion temperature gradient mode

Hongxuan Zhu[1,2], H. Chen[3,4], Z. Lin[4], and A. Bhattacharjee[2]
[1] Zhejiang University, [2] Princeton University, [3] Peking University, [4] University of California, Irvine
e-mail (speaker): hongxuan@zju.edu.cn

Turbulent transport significantly impacts the performance of stellarator magnetic confinement devices. For example, in the Wendelstein 7-X (W7-X) device, the ion-temperature-gradient mode (ITG) is believed to limit the achievable ion temperature in electron-cyclotron-resonance-heated plasmas [1]. To understand and predict turbulent transport in stellarators, many existing gyrokinetic and fluid codes (GTC, GENE, BOUT++, etc.) have been equipped with the capability to simulate turbulence in stellarators. New codes are also being developed. For example, the GPU-based gyrokinetic code GX has been incorporated into the stellarator optimization codes DESC and SIMSOPT, as well as the transport solver T3D to predict the plasma profile evolution in stellarators.

While significant efforts have been made on the numerical front, theoretical understanding of turbulence in stellarator geometries is still not fully explored. It is well known that turbulence is anisotropic in magnetic confinement devices, $l_\parallel \gg l_\perp$, where $l_\parallel$ ($l_\perp$) is the characteristic wavelength along (across) the magnetic fields. Therefore, the fluctuating electrostatic potential Φ can be written as $\hat{\Phi}(\psi,\alpha,l)e^{iS(\psi,\alpha)}$, which consists of a rapidly varying phase factor e^{iS} and a slowly varying envelope $\hat{\Phi}$. Here, ψ is the flux-surface label, α is the field-line label and l is the distance along field lines. In stellarators, field lines at different α couple within flux surfaces due to non-axisymmetry. This effect has often been neglected, but recent simulation results, e.g., from global gyrokinetic codes GTC, EUTERPE and GENE-3D, have shown that the fluctuation level on flux surfaces can be different from local (in α) simulations. A careful study of this effect is thus desired.

In this work [2], we numerically simulate the linear electrostatic ITG eigenmodes in stellarators using the global gyrokinetic particle-in-cell code GTC, and present a theoretical explanation for the observed mode structures. We simulate the precise QA and precise QH configurations reported in [3], as well as a W7-X high-mirror configuration used in [4]. We find that the linear eigenmode structures are nonuniform on flux surfaces and are localized in α at the downstream direction of the ion diamagnetic drift. Based on a simple model from Zocco *et al.* [5] and following the WKB theory of Dewar and Glasser [6], we show that the localization can be explained from the nonzero imaginary part of k_α. Focusing on the precise QA configuration, we further demonstrate that a localized surface-global eigenmode can be constructed from local gyrokinetic codes stella [7] and GX [8], if we first solve the local dispersion relation with real wavenumbers, and then do an analytic continuation to the complex-wavenumber plane. These results suggest that the complex-wavenumber spectra from surface-global effects are required to understand the linear drift-wave eigenmode structures in stellarators.

References
[1] Nucl. Fusion **61**, 116072 (2021).
[2] arXiv:2506.12948.
[3] Phys. Rev. Lett. **128**, 035001 (2022).
[4] J. Plasma Phys. 88 905880310 (2022).
[5] Phys. Plasmas **23**, 082516 (2016); **27**, 022507 (2020).
[6] The Physics of Fluids **26**, 3038 (1983).
[7] J. Comput. Phys. **391**, 365 (2019).
[8] J. Plasma Phys. **90**, 905900402 (2024).

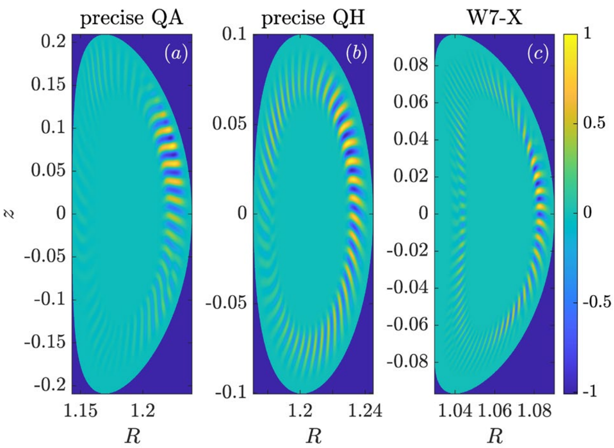

Figure 1. The linear global ITG eigenmode structures at toroidal Boozer angle $\zeta = 0$. Lengths are normalized by an averaged major radius R_0 of each configuration.

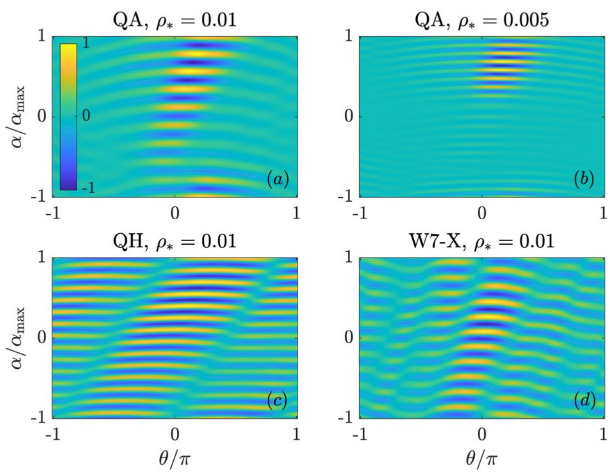

Figure 2. The same eigenmode structures but in field-line following coordinates (α, θ). The mode localization becomes more pronounced at a smaller $\rho_* = \rho_i/a$.