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Exploring Turbulence in Stellarators: Advances in Global Gyrokinetic Simulations

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Magnetic confinement fusion research is progressing toward the realization of fusion power plants. While tokamaks have long been the dominant approach, stellarators such as Wendelstein 7-X (W7-X) are emerging as promising alternatives. W7-X has demonstrated that neoclassical transport can be reduced to levels comparable to those in tokamaks, with microturbulence now becoming the primary performance-limiting factor.

Understanding and controlling turbulence is critical for optimizing stellarators as viable alternatives to tokamaks for future fusion power plants. Thanks to modern supercomputers, advanced gyrokinetic simulations can now probe stellarator turbulence in unprecedented detail. Tools like GENE-3D [1] (Figure 1) extend the well-established GENE code to perform global simulations in non-axisymmetric geometries, providing valuable insights into the dynamics of turbulence in stellarator configurations (Figure 2).

In this work, we present a comprehensive validation of GENE-3D for W7-X, analyzing multiple W7-X discharges [2,3,4]. Our findings reveal that turbulence is not solely driven by ion temperature gradient (ITG) modes — trapped electron mode (TEM) turbulence, primarily fueled by electron temperature gradients, plays a crucial role [2,3]. Additionally, we explore electron temperature gradient (ETG) turbulence, previously considered negligible in W7-X, to investigate its cross-scale interaction with ion-scale modes [5]. We also assess the impact of electromagnetic instabilities, such as kinetic ballooning modes, and examine how the equilibrium radial electric field influences turbulence [4].

Beyond W7-X, we provide confinement predictions for two new quasi-helical stellarator configurations optimized for higher ITG mode thresholds [6]. Finally, we demonstrate how resonant wave-particle interactions between supra-thermal ions and ITG modes can suppress turbulence, thereby improving confinement in future stellarator designs [7]. This work provides a foundation for the development of next-generation stellarators with optimized neoclassical and turbulent transport.

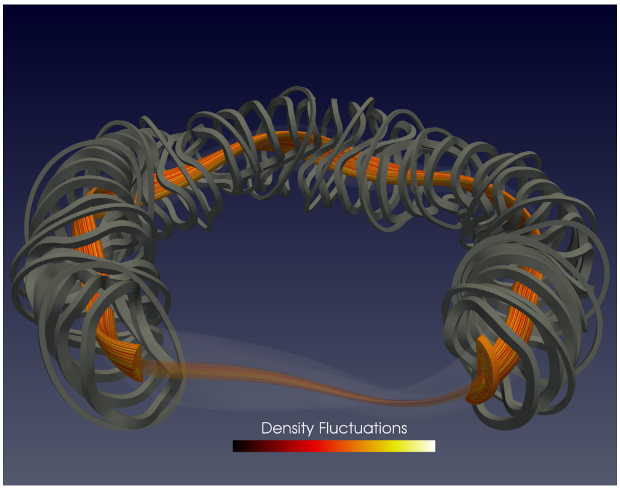

Figure 1. Turbulence in the plasma of the Wendelstein 7-X stellarator, calculated with the GENE-3D code: The magnetic cage generated by the magnetic coils (gray) shapes and confines the plasma. In the plasma cross-section, small eddies — variations in plasma density — are visible.

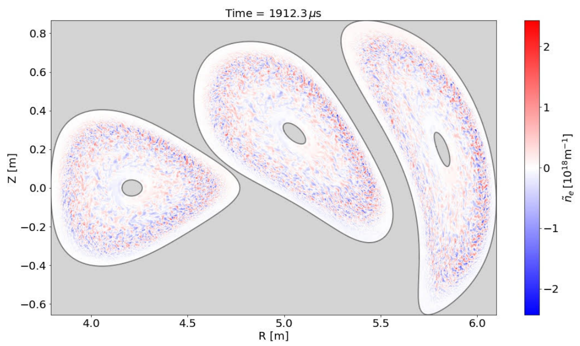

Figure 2. Turbulence calculation with the GENE-3D code for Wendelstein 7-X: The instantaneous snapshot shows vortex-shaped variations of the plasma density across different cross-sections of the plasma.

References

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