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Physics-informed machine learning techniques for edge plasma turbulence modelling in computational theory and experiment

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Edge plasma turbulence is critical to the performance and operation of magnetic confinement fusion devices. Drift-reduced Braginskii two-fluid theory has for decades been widely applied to model boundary plasmas with varying success. Towards better understanding edge turbulence in both theory and experiment, a custom-built physics-informed deep learning framework constrained by partial differential equations is developed to accurately learn turbulent fields consistent with the two-fluid theory from partial observations of electron pressure. This calculation is not otherwise possible using conventional equilibrium models. With this technique, the first direct quantitative comparisons of turbulent field fluctuations between electrostatic two-fluid theory and electromagnetic gyrokinetic modelling are demonstrated with good overall agreement found in magnetized helical plasmas at low normalized pressure.

To translate these computational techniques to experimental fusion plasmas, comprehensive 2-dimensional diagnostics operating on turbulent time scales are necessary. For this purpose, a novel method to translate brightness measurements of HeI line radiation into local plasma fluctuations is demonstrated via a newly created deep learning framework that integrates neutral transport physics and collisional radiative theory for the $3^3D - 2^3P$ transition in atomic helium. Using fast camera data on the Alcator C-Mod tokamak, this thesis presents the first 2-dimensional time-dependent experimental measurements of the turbulent electron density, electron temperature, and neutral density in a fusion plasma using a single spectral line. With this experimentally inferred data, initial estimates of the 2-dimensional turbulent electric field consistent with drift-reduced Braginskii theory under the framework of an axisymmetric fusion plasma with purely toroidal field are calculated. The inclusion of atomic helium effects on particle and energy sources are found to strengthen correlations between the electric field and electron pressure while broadening turbulent field fluctuation amplitudes which impact $\mathbf{E} \times \mathbf{B}$ flows and shearing rates.

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