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AI Surrogate Model for Turbulent Transport in Tokamak Plasmas Using Gyrokinetic Simulation Data and Machine Learning

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Turbulent transport plays a crucial role in determining the confinement properties of tokamak plasmas, directly impacting the efficiency of fusion energy production. Traditional first-principles simulations based on gyrokinetic theory provide high-fidelity predictions but are computationally expensive, limiting their applicability for real-time optimization and control. Artificial intelligence, driven by large-scale data, is becoming increasingly important in magnetic fusion research. In this work, we develop a deep learning-based AI surrogate model to predict turbulent transport properties using data from high-resolution gyrokinetic simulations performed with the GTC code. We explore the plasma gradient space for the Cyclone Base Case and HL-2A parameters using nonlinear gyrokinetic simulations to generate datasets for typical electrostatic drift-wave turbulence. The primary electrostatic modes, ion temperature gradient (ITG) and trapped electron mode (TEM), are classified and labeled using conventional methods. We apply a support vector machine (SVM) with plasma gradients as input to classify drift-wave turbulence types, achieving an accuracy of up to 98%. Simple distance-based formulae for transport coefficients are derived, enabling rapid classification of turbulence types and demonstrating their effectiveness. Furthermore, neural networks and other machine learning techniques are employed to develop surrogate models for turbulent transport across a wide range of tokamak parameters. Our models achieve an R-squared value of up to 0.85 for nonlinear transport and 0.95 for linear growth rates. These results demonstrate that AI-driven models can serve as efficient alternatives to conventional gyrokinetic simulations, enabling faster scenario modeling and facilitating real-time plasma control in future tokamak experiments.

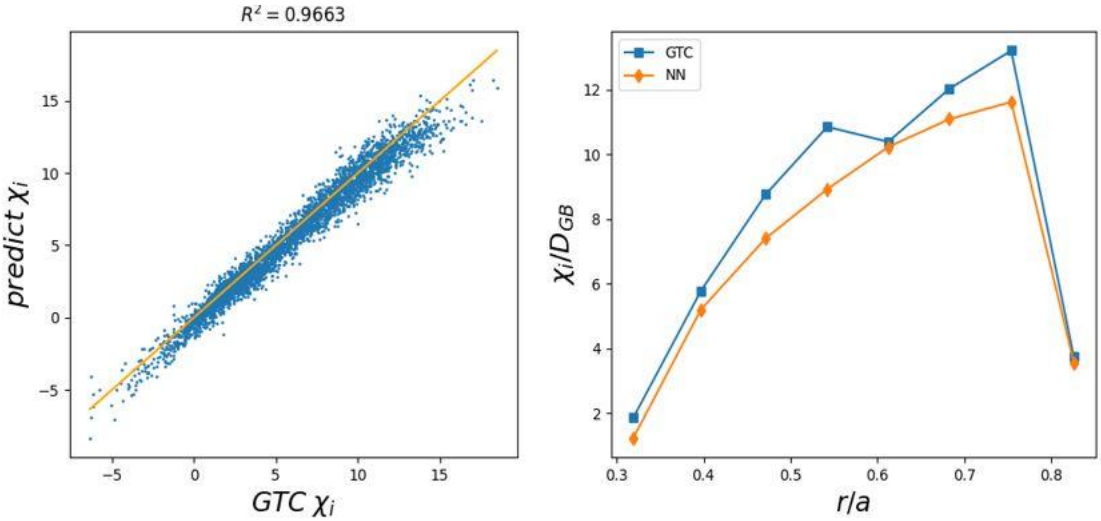

Figure 1: AI surrogate mode for turbulent transport using GTC data and deep learning